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Development of ship fire risk index

Thesis submitted for examination for the degree of Master of Science in Technology.
Turku 25.11.2019
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Diplomityön tiivistelmä

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Tiivistelmä

Yksi yleisimpiä koko risteilylaivaa uhkaavia onnettomuuksia on tulipalo. Uusien risteilylaivojen koko jatkaa kasvuaan. Kun risteilylaivojen koko kasvaa, niin kasvaa laivalla olevien matkustajien lukumääräkin. Suurempi ihmismäärä laivalla johtaa suurempaan riskiin katastrofaalisessa onnettomuudessa. Yleisesti hyväksytty kanta on, että suurempi risteilylaiva tarkoittaa suurempaa riskiä. Toisaalta suuremmalla risteilylaivalla on suurempi mahdollisuus selviytyä onnettomuudesta ja toimia itsessään parhaana pelastusveneenä, niin kuin on tarkoituskin.

Toinen huomionarvoinen asia on, että risteilylaivan koon kasvaessa sen kokonaisvaltaisen palotuvallisuuden käsitteleminen hankaloituu ja siihen liittyvien riskien käsitys hämärtyy. Edellisiin kohtiin perustuen havaittiin tarve työkalulle, jolla voitaisiin arvioida ja verrata risteilylaivojen kokonaisvaltaista paloturvallisuutta.

Tämän diplomityön aikana kehitettiin työkalu, jolla voidaan qvantifioida risteilylaivan kokonaisvaltainen paloturvallisuustaso niin, että sitä voidaan verrata muiden vastaavien risteilylaivojen paloturvallisuustasoon. Malli perustuu paloriski-indeksiin. Malli sisältää kolme moduulia, jotka arvioidaan erikseen; paloturvallisuus-, evakuointi- ja selviytymismoduuli. Moduuleista saadut pistemäärät painotetaan merkitsevyyskertoimella ja tuloksena on kokonaisvaltainen paloturvallisuusindeksi.

Paloturvallisuus- ja selviytymismoduulit toimivat suunnitellusti. Pelastusveneisiin siirtymisen mallintaminen mallille sopivalla tavalla osoittautui haastavaksi, minkä takia evakuointimoduulin viimeisteleminen jätettiin työn seuraavaan vaiheeseen. Joitakin mallin osia tarvitsee käsitellä tulevaisuudessa tarkemmin uudelleen.

Avainsanat Paloturvallisuus, Paloriski-indeksi, Risteilylaivan turvallisuus, monimuuttuja-arviointi

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Abstract of master's thesis

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Abstract

Fire is one of the most common threatening accidents onboard a cruise ship. As cruise ship sizes are growing, as well as the number of passengers onboard, so does the risk in catastrophic accidents. It is widely believed, that larger cruise ships oppose bigger risks. On the other hand, a larger ship has a greater potential to survive accidents and to perform its duty as the best lifeboat itself.

Another aspect of growing cruise ship size is that the perception of the overall fire safety level of the ship becomes difficult to assess, and the perception of the risks involved diminishes. From previous points, a need for a tool, which could be used for assessing and comparing holistic fire safety levels of cruise ships, was recognized.

In this master's thesis, a model was developed to quantify the overall fire safety level of a cruise ship in a manner that enables comparison between fire safety levels of other cruise ships. The model is based on the fire risk indexing method. The model consists of three modules: fire safety, evacuation and resilience, which are evaluated and scored independently. These scores are then weighted, and the overall fire safety score of the ship is obtained.

Fire safety and the resilience modules function as intended. Finalizing of the evacuation module was left out for future work due to difficulty in assessing embarkation reliably with a method suitable for the model. Some parts of the model should be reassessed and looked into in more depth.

Keywords Fire safety, Fire risk index, Cruise ship safety, Multi-attribute evaluation

Aknowledgements

This Master's thesis was done for Meyer Turku Oy in conjunction with continuous efforts to quantify more in depth and to increase the level of cruise ship fire safety. The topic was offered based on my interest in ship safety and fire safety. The purpose of this master's thesis was to try to take a holistic approach in the subject instead of going deep into a single aspect of the cruise ship fire safety. A model to quantify cruise ship fire safety was developed, which also enables comparison between different ships and assessment of design changes' effects on overall fire safety level of the ship in question.

I would like to express my gratitude to Professor Pentti Kujala for supervising this master's thesis and for the much-needed comments and advice. Some national scale pressure in finishing this thesis was useful as well.

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I would also like to thank M.Sc. Juhani Nurmi from Meyer Turku for continuous support and guidance in fire related matters of the thesis. He is also to be thanked for my interest in fire safety in general.

I would also like to thank all the professionals within the industry and academia, who participated in the two-phased questionnaire regarding large fires onboard a cruise ship. Their involvement gave the needed depth and validity for the resilience module.

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Symbols

α	[kW/s^2]	Fire growth coefficient
ρ	[g/m^3]	Density
τ		Decay scaling parameter
τ	[s]	Time constant
χ		Combustion efficiency factor
γ		Percentage of fire load consumed before decay phase
A_o	[m^2]	Area of opening
A_T	[m^2]	Total surface area of the compartment
A	[m^2]	Floor area
a		Constant
CHF	[kW/m^2]	Critical heat flux
c_p	[kJ/g·K]	Specific heat
D	[m]	Diameter of pool fire
D	[pers/m^2]	Population density
E	[min]	Embarkation
FB_{SP}		Fire brigade success probability
F_c	[pers/s]	Calculated flow
F_s	[pers/s/m]	Specific flow
f		Frequency of ignition
H	[m]	Height from fire base to ceiling
H_i	[[MJ/kg]	Heat of combustion of material *i*
H_o	[m]	Height of opening
h_k	[kW/m^2·K]	Effective heat transfer coefficient
k	[kW/m·K]	Thermal conductivity
k		Constant that depends on water mass flux (*Sprinklers*)
k		Constant (*Evacuation*)
L	[m]	Height of pool fire
L	[min]	Launching time (*Evacuation*)
$\dot{m}_a$	[kg/s]	Air mass flow
m	[kg]	Mass of combustible material
n	[min]	Time limit for evacuation
n		Number of attributes (*FRI*)
$P(F_{di})$		Probability of flashover in space *i*, derived from database
$P(F_i)$		Probability of flashover in space *i*
$P(Sdi)$		Probability of fire spread from space *I*, derived from database
$P(Si)$		Probability of fire spread from space *i*
$\dot{Q}$	[kW]	Heat release rate
$\dot{Q}_F$	[kW]	Heat release rate required for flashover
$\dot{Q}_{inc}$	[kW]	Required heat release rate for sustained burning
$\dot{Q}_{max}$	[kW]	Maximum heat release rate
$\dot{Q}_{spr}$	[kW]	Heat release rate when sprinklers are activated
$\dot{Q}_{stoich}$	[kW]	Stochiometric heat release rate
$\dot{Q}_{max}^{(v)}$	[kW]	Maximum heat release rate in ventilation controlled fire
$\dot{q}_e''$	[kW/m^2]	External heat flux

q_{total}	[MJ]	Total fire load
R	[min]	Reaction time
RTI	[$m^{1/2}s^{1/2}$]	Response-time index of the sensor
r	[m]	Radial distance from fire center to detector
r_i		Normalize value of attribute i
S		Fire risk index number
S	[m/s]	Walking speed (*Evacuation*)
S_{AP}		Sprinkler activation probability
S_{RL}		Sprinkler reliability level
s-y		Ship-year
T	[min]	Travel time
TRP	[$kW \cdot s^{1/2}/m^2$]	Thermal response parameter
T_∞	[°C]	Ambient temperature
T_{act}	[s]	Time of sprinkler activation
T_d	[°C]	Sensor temperature
T_g	[K]	Upper layer gas temperature
T_g	[°C]	Hot gas and flame temperature (*Sprinklers*)
T_{ign}	[K]	Ignition temperature
t	[s]	Time from ignition
t_d	[s]	Decay phase start time
t_g	[s]	Growth phase end time
t_{inc}	[s]	Fire incipient phase length
t_{resp}		Response time
t^2		t-squared fire
u	[m/s]	Flow velocity of the hot gases
W_e	[m]	Effective width
w_i		Normalized attribute weight
x_i		Value of attribute i
x_{max}		Maximum value of x_i
x_{min}		Minimum value of x_i
y		Historical ignition frequency
y_i		Raw weight of attribute i (*FRI*)

Abbreviations

AHP	Analytical hierarchy process
ASET	Available safe egress time
CFD	Computational fluid dynamics
CHF	Critical heat flux
CR	Consistency ratio
EU	European Union
FDS	Fire dynamics simulator
FED	Fractional effective dose
FRA	Fire risk assessment
FRI	Fire risk index
FSA	Formal Safety Assessment
FSS	International Code for Fire Safety Systems
FTP	International Code for Application of Fire Test Procedures
HRR	Heat release rate
IMO	International maritime organization
LHS	Latin hypercube sampling
MCDA	Multi-criteria decision-making
MES	Marine evacuation system
MVZ	Main vertical zone
PFS	Probabilistic fire simulator
RBD	Risk-based design
RMS	Royal mail ship
RSET	Required safe egress time
SAFEDOR	Design, Operation and Regulations for Safety
SOLAS	Safety of life at sea
SRTP	Safe return to port
TRP	Thermal response parameter

1 Introduction

Cruise ship sizes, measured with any indicator, have grown rapidly during the last decades. The whole cruise ship industry has grown and evolved, which has led to an increase in competition for customers between cruise lines. This, as well as modern design and production methods has resulted in larger and more complex technical and architectural designs. As sizes and complexity of cruise ships grow, perception of overall fire safety level of the ship diminishes and becomes difficult to rationalize. It is a widely accepted view that as cruise ship sizes and complexity increases, so does the risks involved and the worst-case societal loss becomes more unbearable [1]. On the other hand, the current trend and idea behind the safe-return-to-port (SRTP) regulation is that the ship itself is the best lifeboat. Now it is evident that larger ships, if designed correctly, can take more damage and still stay afloat, and make their way to the nearest harbor. So, the increasing size of cruise ships bring challenges and risks, but possibilities as well.

Fire accidents and flooding cover more than 90 % of accidents that lead to loss of life onboard passenger ships [2]. Eliopoulou et al. [3] investigated safety- and risk levels of world's merchant fleet. It was concluded that fire and explosion events are most frequent accidents leading to total loss of passenger- and cruise ships. The total historical loss frequency of cruise ships due to fire or explosion was calculated to be 4.77E-04. Exactly the same frequency was observed for passenger fatalities per ship-year. When compared to former investigations, the frequency of fires and explosions have grown. One explaining factor was noted to be difficulties in fire control in complex and compartmented spaces, which are commonly found in today's ships. It is evident that fire safety is a key factor in cruise ship design, which should be considered in all decisions.

The fire safety level of a cruise ship is currently built into deterministic rules and regulations. As a result, the overall fire safety level of the ship is unknown. Another point is that as fire safety rules are prescriptive, they are seen as a constraint instead of a design feature or a goal. Due to these realizations, interest towards risk-based fire safety regulations, similar to probabilistic damage stability rules, have emerged during the past two decades. Such regulations would also enable comparison between fire safety levels of different ships, and, if the procedure is simple enough, quantification of the effects of different design solutions to fire safety level of the ship.

Currently the above described risk-based regulations or tools to quantify overall fire safety level of a cruise ship do not exist. Extensive formal risk assessments (FSA) can be used to determine good approximation about the overall fire safety level for a given ship. FSA processes are, however, laborious and time-consuming and thus cannot be used to systematically compare fire safety levels of multiple ships, or the effects of different designs to the fire safety level of the ship under design. The purpose of this thesis is to develop a model, which would enable such comparisons.

1.1 Research problem and goals

The main goal of this master's thesis is to develop a model to evaluate holistic overall cruise ship fire safety and to identify the attributes needed for such a model. The model is intended to be used in a comparative manner in the concept design phase to evaluate the effect of different design solutions in the fire safety level of the ship, as well as to compare different ships with each other. The use in the concept phase sets limitations and requirements for the development of the model. Firstly, available data is limited, not much is known about the ship and its' final form at this phase. Also, designs in the concept phase change quickly and often, thus the model should be quick and easy to use. If extensive labor is required, the model will not be used.

In this master's thesis the framework and construction of the model, as well as the attributes that are to be used in the model, are the most important aspects. The model should respond to design changes in a predictable and meaningful manner. The most relevant attributes should be adjustable, so that new or improved systems or methods can be taken into account. However, the model developed in this master's thesis does not try to form actual, realistic fire safety assessment or an index, like the FN-curve. As far as applicable at this point, realistic historical data, formulation and best practices are used, even though realistic representation of the fire safety level is not sought after. Realistic representation of overall fire safety level of the cruise ship is too a large, broad and complex topic to tackle with available resources. Currently, the model is meant for comparative purposes only. Updates to the model should however be plausible in the future. In the future, the model could be updated and modified in the direction of a more realistic fire safety assessment.

Based on Meyer Turku's expert judgement, the model should consider at least the following attributes:

- Fire ignition
- Fire spread into adjacent spaces
- Evacuation from initial space
- Evacuation to assembly stations
- Evacuation to lifeboats or to a MES

One important consideration about the scope of the thesis is that the main purpose is to develop the model and the framework around it. Single aspects of the model are addressed in as much of detail, as time restraints allow. However, producing a functional model is more important than accuracy and reliability of individual components of the model, at this phase. The idea is that individual parts of the model can be fine-tuned and improved in the future, for example as a part of other master's theses or as a normal work task at Meyer Turku.

1.2 Limitations

Due to the broad nature of the thesis topic and the limited time available for the execution, multiple limitations are set for the thesis. These limitations are explained and discussed in this section.

1.2.1 Fire size

After initial familiarization with the subject of the thesis and previous research conducted on the area, it became clear, that the modelling or simulating of fire spread from compartment to compartment would not be feasible. The number of variables and uncertainties rise exponentially, if fire spread from compartment to compartment is assessed in application as the one presented in this thesis.

As a result, only fires in initial compartment are taken into account in the simulations. The need to assess large fires was recognized as well. Thus, the resilience module was implemented into the model. The resilience module deals with the ship's operational capability after large 1 - 2 MVZ fire. Fire sizes, which fall between the fire in initial compartment and 1- 2 MVZ, would require fire spread simulation from compartment to compartment. Not including mid-scale fire into the model is also supported from the operational point of view.

The most likely outcome from fire, which destroys the initial compartment, is that the MVZ, where the compartment is located, is evacuated to adjacent MVZs. Thus, if the fire spreads to adjacent compartments, the compartment can be assumed to be empty of people. Then again, the whole ship would be most likely evacuated in case of 1 - 2 MVZ fire, however, SRTP regulations require that the ship can sail to the nearest harbor after one MVZ has burned. Based on these assumptions, mid-scale fires are not of biggest interest, as their effect on ship operation and human safety are not as critical.

1.2.2 The effect of fire on people

At this point it was decided that fire effects on people would not be included in the model. Thus, no fractional effective dose (FED) calculations or F-N curves would be produced. The effect on people will most probably be included in the model in future development. Also, regarding evacuation, no interaction between fire and people would be taken into account.

1.2.3 The effect of fire on structures

The effect of fire on the structures of the ship is not taken into account in the model. The topic itself is complex and difficult, even if the actual structure is known. Taking the structural effects of the fire into account in a model that is intended to represent the whole ship and is used in concept design phase where no structural design is conducted, is merely impossible.

1.2.4 Financial aspects

Another limitation is the exclusion of financial aspects of the fire. Assessing the financial aspects of fires are not of biggest interest from the perspective of the shipyard, which is only concerned about the safety of persons onboard a ship. Assessing financial outcomes of the fires would also be difficult within the scope of this thesis. Financial loss caused by a fire is of course largely depended on the size, location and durability of the fire. In practice, all sizes of fires should be simulated, including the mid-sized ones, which were excluded from the scope of the thesis. Also, time restraints of the thesis were considered, when financial aspect was ruled out from the scope of the thesis.

1.2.5 Intentional fires

Intentionally ignited fires are not included in the scope of the thesis or into the model. Predicting consequences of intentional fire is even more difficult than those of unintentional fires. Historical ignition frequencies of course might include some intentional fires, but these are, however, unlikely. Due to the above-mentioned reasons, intentional fires were ruled out from the scope of the thesis.

1.3 Structure of the thesis

After the introduction, fire safety onboard a cruise ship is explained in short. Fire safety of ships will be dealt with in this thesis, thus more emphasis on items, which are relevant to this thesis are discussed. Some new trends and efforts towards probabilistic fire safety regulations are also dealt with. In the following chapter the theory behind individual components of the model constructed is explained and commented on. After theory, the scientific methods, which are used in the model, are explained and their suitability is evaluated.

In the model development chapter, the structure of the model and its components are explained. Also, implementation of the theory and method in the model are explained for the cases where more in-depth explanation is required. Simple applications of formulae are not dealt with in detail.

Model sensitivity regarding its different main parameters is studied and dealt with in its own chapter. The purpose is to verify that the model functions logically and satisfies the requirements that are set for it. Main interest is in the effect of parameters that can be adjusted based on the design and components used in the ship in question.

After model sensitivity, future improvements, refinements and add-ons are discussed. Due to the broad and complex topic of the thesis and given the available time for the execution, some components and parts of the model could be improved. Improvements are required especially if actual, realistic fire risk figures would be the goal of the model in the future.

In the discussion chapter some points of the model and process behind it are dealt with. Finally, in the summary, the process and the results are summarized.

2 Fire safety onboard a cruise ship

Safety of Life at Sea (SOLAS) [4] sets minimum safety standards for merchant ships to ensure safe operation and navigation. SOLAS sets minimum standards for construction, equipment and operation for merchant ships. Each flag state that has signed the SOLAS agreement is required to ensure that the ships built in each state are built according to the regulations of SOLAS. As of present, most flag states have outsourced much of this supervising to the classification societies. The first version was published in 1914 after the sinking of RMS Titanic. It has been amended multiple times since. Most often ratifications have taken place after major accidents. Chapter II-2 - Fire protection, fire detection and fire extinction set the requirements regarding fire safety. Functional fire safety objectives of SOLAS are:

1. Division of the ship into main vertical and horizontal zones by thermal and structural boundaries
2. Separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries
3. Restricted use of combustible materials
4. Detection of any fire in the zone of origin
5. Containment and extinction of any fire in the space of origin
6. Protection of means of escape and access for fire fighting
7. Ready availability of fire-extinguishing appliances; and
8. Minimization of possibility of ignition of flammable cargo vapor

Besides direct requirements, Chapter II – 2 obligates to follow the International Code for Application of Fire Test Procedures (FTP) [5] and the International Code for Fire Safety Systems (FSS) [6].

The main purpose of the FTP code is to set regulations and requirements for testing and evaluating parts and components designed to be used in ships. This means that each component or part assembled or built into the ship must have a certification that proves that the item satisfies the FTP code. An alternative procedure for unique designs or solutions is to individually evaluate the system according to the criteria set by the FTP code. MSC convention 88 held in 2010 made proceedings of the FTP code mandatory under the Chapter II-2.

FSS is described as follows: *"The purpose of this Code is to provide international standards of specific engineering specifications for fire safety systems required by chapter II-2 of the International Convention for the Safety of Life at Sea (SOLAS), 1974, as amended"*[6]. In short, FSS sets strict requirements and standards for fire safety equipment and systems. FSS concentrates mostly in fire extinguishing systems and fire extinguishing medias used, for these examples and standards are presented. Despite the strict standards and requirements, the implementation of modern technology is enabled by allowing alternative designs if proved equivalent or safer than accepted alternatives. The FSS has been updated several times, often after major fire on ship accidents.

The above-mentioned documents induce requirements mostly relating to the construction and outfitting of the ship. SOLAS and its amendments also set requirements for safety management, crew training and alertness. These human factors have shown to be crucial for overall safety and fire safety of the ship. Eliopuolou et al. [7] found that over 80 % of marine accidents occur due to human factors. It was stated that safety measures addressed, relating to ship operation, were far more efficient in reducing accident frequencies, than those relating to ship construction and equipment onboard. Requirements relating to construction and equipment were found to have a larger effect on the scale of the accidents.

In general, fire safety can be divided in two categories; active and passive. Active fire safety systems are reactive attempts to prevent or extinguish the fire, such as automatic fire extinguishing systems and the action of firefighters. Passive fire safety systems are measures that are built in a building or in a ship, which are meant to prevent or to control the fire. An example would be dividing boundaries between spaces that prevent fire from spreading from space of ignition to adjacent spaces.

Fire safety systems required by the above-mentioned documents can also be divided in active and passive systems. Active fire safety systems include automatic fire detection and alarm, sprinkler systems and actions of onsite crew staff and actions of the crew fire brigade. Passive systems include everything from evacuation and fire control plans to sub-divisioning of the ship by fire categorized bulkheads and decks. Also, the amount of combustibles is limited by the SOLAS space categorization. This controls the ignition frequency and the intensity of the plausible fire.

2.1 Current trends

Modern technology and design tools enable novel and innovative solutions and designs, which are not in line with prescriptive rules, but are equally, or even more safe. In order to enable such solutions and designs, Guidelines on Alternative Design and Arrangements for Fire Safety were published in MSC/Circular 1002 [8]. These guidelines enable the usage of performance-based design. The basic principle is that the design team must prove by engineering analysis that their design is as safe, of safer than a comparable design, which is compliant with prescriptive rules. If no comparable design can be found, the procedure requires the design team to perform safety analyses in order to prove the safety of the design. In the case of a space on the ship, the purpose of the analysis is to ensure that the design enables evacuation of the space in question with no casualties in every fire scenario. Depending on the application and difficulty of the alternative design, various levels of acceptance procedures are used. Each alternative design is treated case by case.

Interest in more goal-based safety regulations has been evident. It is thought that more goal-based regulations would enforce new and innovative solutions and enable the use of safety as a design parameter instead of a constraint. The probabilistic damage stability concept was the first attempt towards goal-based regulations. In the early 1960's, the probabilistic damage stability concept was introduced for the first time by Kurt Wendel. The concept gained big interest and acceptance and was developed further and interpreted as an alternative damage stability approach for deterministic rules for passenger ships in 1974. The method was implemented as mandatory in the SOLAS in 2009. Wendel's concept acted as an initiating event for the interest in risk-based design (RBD). [9]. Probabilistic damage stability calculations can be thought of as a as a way of quantifying the ship's stability performance index in the context of hull damage case. As such, Wendel's concept was first attempted in quantifying a specific ship-level risk.

Interest in other similar goal-based rules has been on the table as well. The European Union (EU)-funded research project Design, Operation and Regulations for Safety (SAFEDOR), was initiated to develop a risk-based regulatory framework. The need for a risk-based regulatory framework was realized as old deterministic rules prevented new and innovative, but safe, solutions that modern state-of-the-art design and analysis methods made possible. Another key point of SAFEDOR was also to introduce safety as an objective of design instead of a constraint. [10].

Even though fire safety was a part of the SAFEDOR, afterwards another EU-funded research project, FIREPROOF, was initiated. The aim of the project was to develop the basis and the procedures for probabilistic fire safety regulations, similar to probabilistic damage stability rules. The project was divided in four work packages: scenario generation; consequence assessment; implementation and benchmarking; and probabilistic fire safety regulations [11]. From these, so far only the first two were addressed during the active phase of the project [11]. The results and findings of relevant parts from SAFEDOR and FIREPROOF are more discussed later, under their specific topics.

3 Methods

In this section the methods used in the model development are presented.

3.1 Fire risk indexing

Fire risk indexing (FRI), also known as risk ranking, point schemes, numerical grading and rating schedules, is a heuristic method for addressing fire safety. It is cited as a link between fire science and fire safety. FRI is a form of multi-criteria decision analysis (MCDA). The idea of FRI is to create a single index number which reflects the relative fire safety level of the system. This index number is then compared to other designs, or to a standard. In many applications some knowledge in and understanding of the fire safety level of the system is required, but formal quantitative fire risk assessment (FRA) is not a sensible option due to financial or timely resources. In these applications FRI can offer a meaningful and cost-effective, but a little less sophisticated alternative. FRI also enables a straightforward way of implementing qualitative attributes to the evaluation. [12]. Despite the lack of sophistication required for formal FRA, indexing is considered valuable and an efficient method for decision-making, should more detailed fire risk analysis be needed [13].

Modern multi-criteria decision analysis (MCDA) originates from operational research and management science. MCDA is a widely accepted and researched method in aiding decision-making and design-comparison, but it has its limitations of course. MCDA tries to offer tools for problems, where multiple attributes need to be weighted and considered in decision-making or in design. In a real-world application, data and information are often limited, incomplete or sparse, or a combination of these. In addition, some of the attributes are favorable and some are negative considering the end goal. Dealing with such data is one of the key aspects of MCDA. Dealing with the type of data mentioned above is present in most fields of society, which has led to a broad number of applications of MCDA. Insurance, financial and risk-related fields e.g., widely use MCDA. [14]. Due to a vast number of different applications, a great variety of methods and tools have been developed. Only some of these are applicable in FRI context. In this chapter only aspects of MCDA relating to FRI are discussed.

3.1.1 Generalized fire index procedure

FRI methods vary in structure, methods and applicability, as each application have their own attributes, attribute weightings and focuses. The focus, or the end goal of FRI can be, for example, financial loss, safety of human life, property loss or a combination of these. Due to the nature of FRI, each method or process has been developed for a specific purpose for a specific application. A method for a holistic passenger ship FRI has not been presented at the time of writing this thesis.

Watts [15] presented generalized procedure for the construction of FRI in a building environment, which is used as a reference in this section, if not mentioned otherwise. Later in SFPE Handbook of Fire Protection Engineering [12], Watts simplified the procedure steps to a more general format. Watts' generalized procedure explains well and in a simple manner the idea and execution of FRI. The original generalized procedure for FRI in building environment is presented below, as it is more explanatory and describes the attributes that are also present in this master's thesis.

Step 1. Identify the set of attributes that characterize fire safety in the group of buildings to be evaluated.

Step 2. Develop an importance weight for each attribute.

Step 3. Develop methods for assigning values to each attribute for each building.

Step 4. Select evaluation model.

Step 5. Validate and calibrate the evaluation procedure.

First, attributes that will be used in FRI are selected. These attributes depend on the application and should be selected carefully. Attributes can vary from ignition frequency, fire suppression systems to population within the premises and average evacuation distance. As of, attributes can be positive or negative in relation to fire risk. Watts states that *"Selection of attributes should result in a set that is nonconflicting, coherent and logical."*, and *"In the final analysis, it is most important that the evaluation vector include only those attributes that vary significantly among the buildings and for which the variation is considered meaningful."*. This means that the attribute list should not include attributes that only single, or a few of the compared systems possesses. Nor should it include attributes that are irrelevant from the fire risk perspective.

Next, an importance weight for each attribute is generated. In relation to fire safety and in focus of the FRI, all attributes are not equally important. By developing weighed values for each attribute, the importance of each attribute in relation to others is determined. This makes weight value generation a crucial part of the FRI. Watts also states that attribute weights should be normalized to sum to one, for which the following formulae is used:

$$w_i = \frac{y_i}{\sum^{n} y_i} \tag{1}$$

And

$$\sum_{:-1}^{n} w_i = 1 \tag{2}$$

Where: w_i = Normalized attribute weight
y_i = Raw weight of attribute i
n = Number of attributes

There are numerous ways to determine weight values for attributes. It should be kept in mind that weight value determination procedures should be systematic and logical, and they should reflect the fire safety goals of the FRI.

In the third step, procedures for assigning values to attributes is developed. The value of an attribute reflects the scale of the effect of the attribute to the fire safety of the system. As mentioned before, the effect can be positive or negative. In order to enable comparison between different attributes, all attributes must be quantified into numerical form. Quantitative measures are easy to express in numbers. In order to enable the comparison of qualitative attributes between other qualitative and quantitative attributes, some sort of scaling process is needed. Likert scale [16] is widely used, where attributes are scaled from 1 to 5, where 1 is the most negative and 5 is the most positive grade. When determining which number each attribute is assigned, expert judgement, Delphi exercise, or some structured method like Analytical Hierarchy Process (AHP) or decision tables, for example, can be used.

As quantitative attributes generally have different units of measure, attributes must be normalized to a dimensionless form. Watts states that general linear normalization is mostly used, which can be expressed as:

$$r_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{3}$$

Where: r_i = Normalize value of attribute i
x_i = Value of attribute i
x_{min} = Minimum value of x_i
x_{max} = Maximum value of x_i

If minimum value of x_i is 0, then normalized value is obtained as:

$$r_i = \frac{x_i}{x_{\max}} \tag{4}$$

When quantitative values are normalized, they vary between 0 and 1. To enable comparison between quantitative and qualitative values, normalized quantitative values must be multiplied with the maximum number of the scale used for qualitative attributes. So, if Likert scale from 1 to 5 is used for qualitative attributes, the normalized quantitative values need to be multiplied with the value 5. Another option is to divide quantitative values with the value 5, which causes values to vary between 0 and 1. The goal in both methods is to enable straight numerical comparison between qualitative and quantitative attributes.

Actual FRI is then calculated using attained attribute values and weights. Several methods for calculating final index number exist. The most simple one is additive weight method, where a normalized value of an attribute is multiplied with the weight of the attribute and all attained values are summed. Additive weight method can be expressed as:

$$S = \sum^{n} w_i r_i \tag{5}$$

Where: S = Fire risk index number

3.2 Analytical hierarchy process

Analytical Hierarchy Process (AHP) was developed by Saaty in 1980 [17]. AHP is a tool for generating ratios or importance factors. The main idea behind the AHP is that it can be used to compare qualitative and quantitative attributes, which is otherwise difficult or impossible in a rational manner. AHP can be used in many various applications, but it has been most common in multi-criteria analyses, planning, resource allocation and in conflict resolution. [18]. In this thesis AHP will be used for the generation of FRI attribute weight values, thus AHP is explained from the viewpoint of multi-criteria analysis. The key item in this thesis is to compare quantitative and qualitative attributes, which led to the use of AHP.

AHP is a straightforward process. In a simple case of generation of weighing factors for attributes, each attribute is compared to other attributes in pairwise comparisons on a predefined scale, using an evaluation matrix. The scale to be used in the comparison is presented below, in Table 1. The scale was created by Saaty in his original work. It has been widely used ever since in AHP applications [18]. An illustrative comparison matrix is presented in Table 2. The comparison is a matter of preference. The person comparing the attributes chooses which attribute is more favored and how much over the other. In practice, this means that the person doing the evaluation should possess extensive knowledge and experience in the subject under consideration. One approach is also to ask multiple professionals to perform the same evaluation and then find similarities or averages from the collected answers.

Table 1. The fundamental scale, reproduced and simplified from [18]**.**

Intensity of importance on an absolute scale	Definitions	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2.4.6.8	Intermediate values between the two adjacent judgements	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	
Rationals	Rations arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Even finer scale 1.1, 1.2…, can be used if compared elements are closer than indicated by the scale

In the matrix, each attribute is compared, and preference of one attribute over another is expressed numerically according to the scale provided above. It should be noted, that the matrix is always symmetric, thus once attributes i and k have been compared, and value have been given for preference for i over k, say 7, reciprocal 1/7 will be automatically given for comparison $k - i$. The matrix is also always an identity matrix, as all its diagonal elements are formed by the comparisons between the same attribute. The value from comparison k - k is naturally always 1.

Table 2. Evaluation matrix.

Attribute	*i*	*j*	*k*	*n*
i	1	1/3	7	1/9
j	3	1	5	1
k	1/7	1/5	1	3
n	9	1	1/3	1

Weight values for different attributes are then calculated by using the eigenvector method. To simplify the process, the power method is often used. Solving the weight values is explained more thoroughly in [18]. More detailed description of the power method is presented in [19].

3.3 Probabilistic fire simulator

Probabilistic fire simulator (PFS) was developed by VTT [20]. PFS is an Excel-based tool, which generates fire scenarios based on user input. If needed, PFS also automatically generates FDS or CFAST input files for each fire scenario. The core of the tool is in random sampling of parameters. Latin Hypercube Sampling (LHS) is mostly used. By assigning probability distributions for parameters affecting the fire scenario and selecting values randomly from the distributions, probabilistic calculations can be made. PFS does not have any pre-built fire models. The user needs to create the fire scenarios, i.e. mathematically model the fire scenarios and determine the parameters to be sampled. Once the mathematical model is constructed, the user can determine the amount of iterations.

As a part of this thesis, PFS workbook was built. In the workbook, compartment fire phenomena are mathematically modelled, including the effects of suppressive actions. The PFS creates the pre-determined amount of design fires. When some measurable objectives are determined, and whether the objective was realized or not within each simulation, the outcome is recorded and a certain type of database is created. Based on this database, probabilities of occurrences of the measured objectives can be derived. In the above-described way, PFS is used to create a database of outcomes from different fires, which is then used to determine probabilities of threatening fire events within spaces onboard a cruise ship. In the following sections 4 - 4.3 the mathematical modelling of fire is discussed in more detail.

4 Theory and previous research

In this section relevant previous research related to similar holistic fire safety models and individual components of the developed model are presented.

The presented ignition frequencies are obtained from statistics of cruise ship fires. Compartment fire modeling formulae is obtained from land-based applications. It should be noted, that most formulae, especially the ones concerning fully grown fires and flashovers, are not designed or verified for modeling fires in large spaces, like atriums found in cruise ships. In this thesis, the presented formulae are used for all spaces onboard. In the future development, if new formulae or alternative methods are available, a more suitable approach for large spaces should be adopted.

4.1 Fire ignition frequency

Fire ignition frequencies onboard passenger- and cruise ships have been studied in multiple researches [7,21,22]. Ignition frequency is commonly assessed by using historical statistics. Ventikos [22] performed comprehensive statistical analysis on fire incidents and accidents as a part of the FIREPROOF research project. The analysis included 1521 records and covers 463 ship-years of passenger- and cruise ship operation. The results are discussed in the original document, but are analyzed more thoroughly in the FIREPROOF report [23], which presents the ignition model developed for the project. Guarin [24] carried out similar review of historical cruise ship fire accident and incident data. Fire ignition occurrences for the top ten spaces with highest ignition frequencies, based on the use of the space, are presented below. The results from Ventikos are presented in Figure 1 and the results from Guarin in Figure 2. The results from both reviews are quite similar with exceptions on public spaces and corridors. It can be concluded, that the pareto principle holds true well for fire ignitions. About 80 % of fires originates from roughly 20 % of spaces [24].

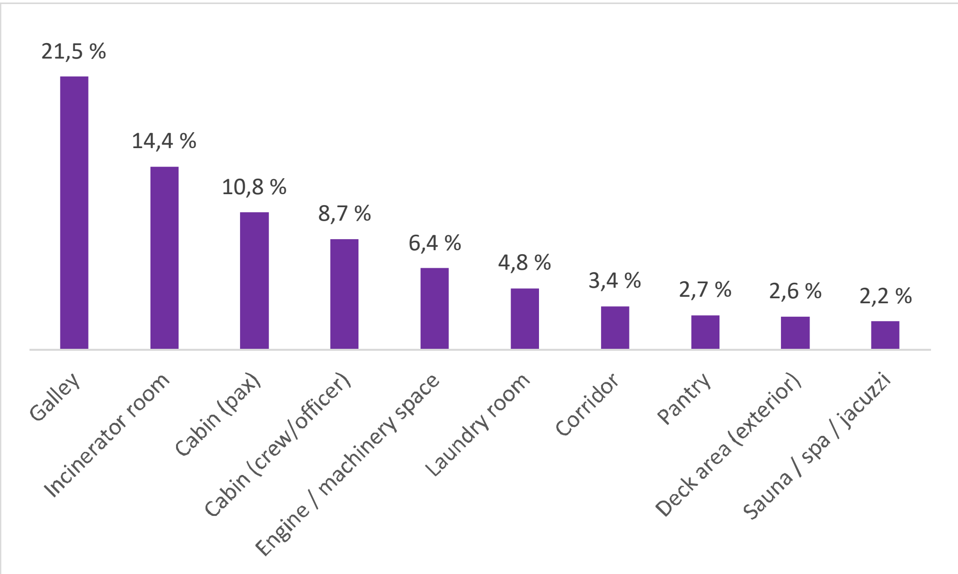

Figure 1. Relative frequency of occurrence, FIREPROOF, reproduced from [23].

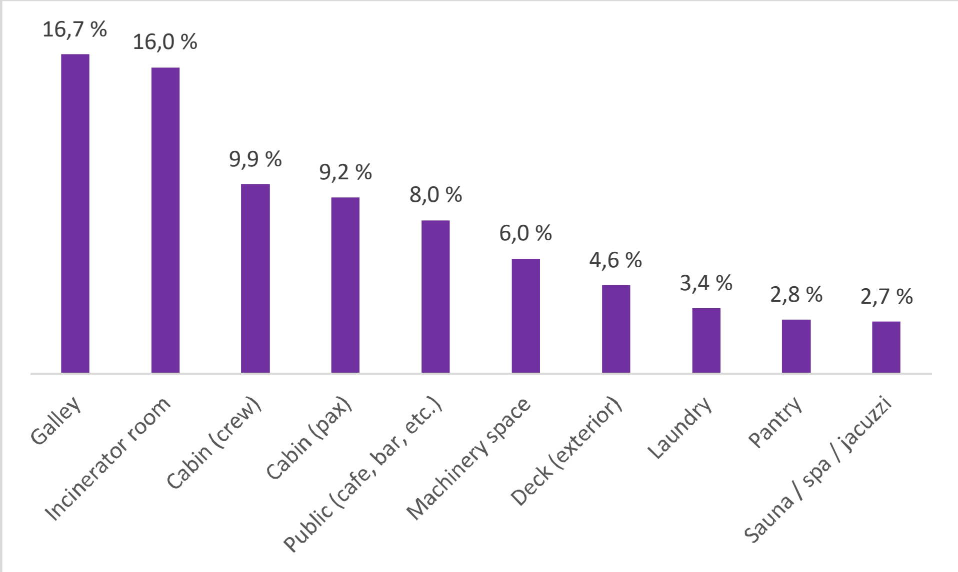

Figure 2. Relative frequency of occurrence, Guarin, reproduced from [24]**.**

Each space onboard a ship is categorized according to SOLAS space categories, presented in Table 3. As the categories reflect certain types of spaces, and are designed with the fire risk in mind, in the literature, ignition frequencies are most often expressed individually for each SOLAS space category.

Table 3. SOLAS space categories, reproduced from [4]**.**

Number	Definition
1	Control station
2	Stairway
3	Corridors
4	Evacuation station and external escape routes
5	Open deck spaces
6	Accommodation spaces for minor fire risk
7	Accommodation spaces for moderate fire risk
8	Accommodation spaces for greater fire risk
9	Sanitary, and similar spaces
10	Tanks, voids and auxiliary machinery spaces having little or no fire risk
11	Auxiliary machinery spaces, cargo spaces, cargo and other oil tanks and other similar spaces of moderate fire risk
12	Machinery spaces and main galleys
13	Store-rooms, workshops, pantries, etc.
14	Other spaces in which flammable liquids are stowed

Typically, when ignition frequency is derived for a single space, the floor area of the space is incorporated in the mathematical formulation [24-26]. The way how the floor area is implemented varies. Guarin [24] introduced the formulation shown in Equation 6, which simply multiplies the floor area of the space with SOLAS category-specific ignition frequency per unit area. Themelis et al. [23] use the same formulation, however, based on large example cruise ships, they found that there is very little correlation with fire ignition frequency and the floor area of a given space. In a building-based study, Tillander obtained similar results, which are in agreement with the assumption that the fire ignition frequency is not linearly depended on the floor area of the space in question [25]. To overcome the issue with the lack of correlation, Themelis et al. derived equation 7. The equation uses the typical floor area of each SOLAS category space. Typical floor areas were calculated individually for each example ship. It was observed, that Rayleigh distribution fits well to the distribution of floor areas of different spaces within the same SOLAS category. From Rayleigh distributions, the 50-th percentile was selected to present a typical floor area. As Rayleigh distribution is asymmetric, the 50-th percentile does not mean the average floor area, but usually a slightly larger area. As a result, three ignition frequencies per SOLAS category space were obtained. From these three, the highest value was selected to be used in the calculations. The selected ignition frequencies were compared against the values obtained from the building industry's spaces for similar uses. The comparison revealed some contradictories amongst the ignition frequencies. Further work with validation was proposed. [23].

$$f_i = y_i A_i \tag{6}$$

Where: f_i = Frequency of ignition in a specific space
y_i = Historical ignition frequency of given SOLAS category space per unit area
A_i = Floor area of the specific space

$$\gamma_i = \frac{frequency\ of\ ignition}{s\text{-}y \times (n_i \times A_{typical\,i})} \tag{7}$$

Where: γ_i = Historical frequency of ignition per SOLAS category (ignition frequency / s-y / m^2)
s-y = Ship-year
n_i = Number of spaces of SOLAS category i

Expected ignition frequencies, derived from FIREPROOF database and ignition frequencies calculated using equation 7 and procedure described above, are presented in Table 4.

Table 4. Ignition frequencies [23].

SOALS space category	Number of occurrences	Expected Frequency of ignition / s-y	Selected ignition frequency γ [s-y / m^2]
1	0	0.000	0.000E+00
2	23	0.050	4.547E-05
3	52	0.112	3.880E-05
4	11	0.024	0.000E+00
5	72	0.155	6.804E-05
6	315	0.680	7.905E-05
7	19	0.041	6.156E-05
8	192	0.415	1.007E-04
9	55	0.119	3.216E-04
10	10	0.022	1.302E-05
11	0	0.000	0.000E+00
12	642	1.386	8.012E-04
13	126	0.272	2.022E-04
14	4	0.009	2.622E-04

It should be noted, that the ignition frequencies presented above do not take into account the severity of fire. Most of the ignited fires are suppressed by the crew even before the alarm is activated.

4.2 Fire within space of ignition

Fire within a compartment can be divided in four phases; growth, flashover, fully developed and decay. The following explanation includes an assumption that no effort to suppress the fire is taken. The growth phase starts with an incipient phase, where the fire grows linearly into state, where it can sustain independent burning. Fizgerald [27] determined that self-sustaining fire is about 20 kW, which corresponds to about 25 cm flame height. After reaching independent burning, depending on the burning material and ventilation conditions, fire grows exponentially. If a sufficient amount of fuel and oxygen is available, a flashover eventually occurs, and fire will develop into a fully developed phase. In a fully developed phase, fire will burn as oxygen or fuel-surface controlled with relatively constant HRR. After a critical amount of fuel load has been consumed, the decay phase starts. The development can be seen in the form of an HRR curve below, in Figure 3. [28]. In the following subchapters, each phase will be addressed in more detail.

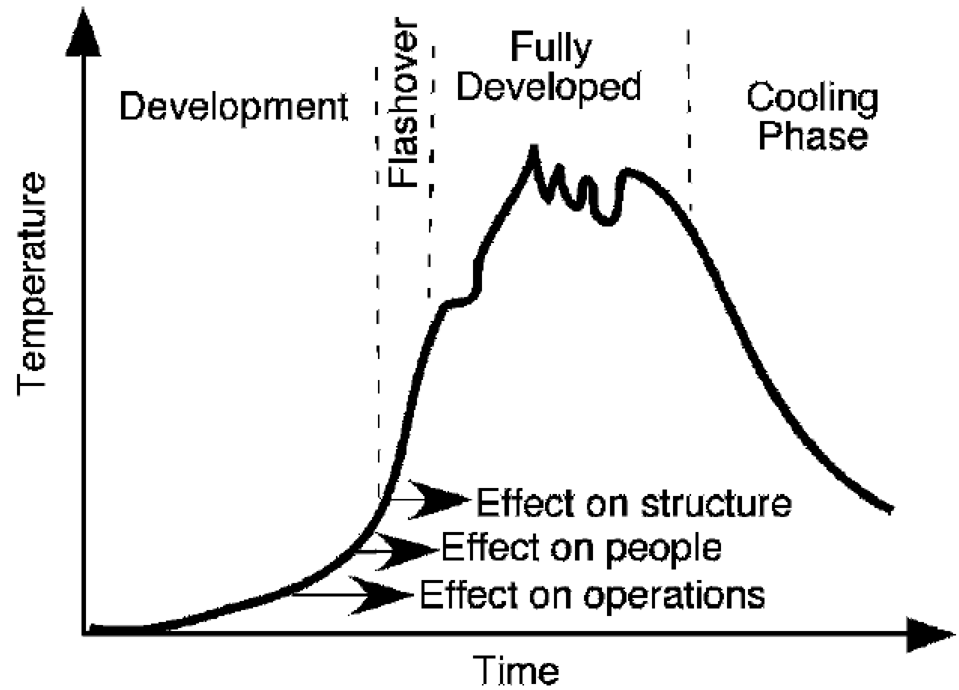

Figure 3. Compartment fire development [28].

4.2.1 Fuel load

Fuel load describes the amount of energy that would be released in a perfect combustion of all combustibles within the compartment. The temperature during the fire depends heavily on the fuel load within the compartment, thus assessing fuel load is important when time-temperature curves are assessed. [29].

The fuel load depends on the mass and net heat of combustion values of the items in the compartment. Net heat of combustion depends on calorific value of the material in question. Fuel load density will be used in the model. Fuel load density q is obtained as shown in equation 8. [29].

$$q = \frac{\sum_i m_i \cdot H_i}{A} \tag{8}$$

Where: m_i = Mass of combustible material i [kg]
H_i = Heat of combustion of material i [MJ/kg]
A = Floor area of the compartment [m^2]

The total fuel load within the compartment is the one obtained using equation 9.

$$Q = q \cdot A \tag{9}$$

As fires are assumed to be oxygen-controlled in the model, the fuel load of the compartment affects only in length of the fire. If the fires would be modelled as fuel-surface-controlled, the HRR development would also be fuel load depended.

4.2.2 Incipient phase

Ignition can be piloted or spontaneous. In piloted ignition the external heat flux is present, which then ignites a component or components within the compartment. In spontaneous ignition the heat accumulates within an object or on a surface, leading to a longer incipient phase.

When ignition has occurred, heat flux is established. Ignition within a compartment does not necessarily lead to flaming combustion. For example, depending on the material, a cigarette might ignite smoldering fire, which decays before flaming combustion is achieved. A heat release rate of 20 kW corresponds to approximately 25 cm flaming fire, which can be considered as self-sustaining fire [30].

The length of the incipient phase depends on the power of the ignition source; materials and conditions within the compartment and mainly on the availability of oxygen. Even though the heat release rate during the incipient stage does not threaten the compartment, toxic gases can be produced, which can affect occupants [23]. Also, depending on the type of the incipient phase, it can also affect detection times of heat or smoke detectors.

When the ignitability of solid materials is addressed, they can be classified as thermally "thin" or "thick". Most of the materials found onboard ships can be taken as thermally "thick". [31]. Tewarson [32] presented a straightforward method to calculate the length of the incipient phase for thermally "thick" materials. The method is based on solving the required time to heat an object above its critical heat flux (CHF). Once the CHF has been reached, the object starts to burn. The CHF of individual materials or objects can be tested using heat release rate apparatuses. The length of the incipient phase, t_{inc} can be approximated using equation 10. When a solid is heated, the rate at which heat transfers to materials depends on multiple material-specific parameters. These parameters are taken into account in the thermal response parameter (TRP). The TRP of a given material is calculated with equation 11.

$$t_{inc} = \left(\frac{TRP}{\dot{q}_e^{"} - CHF} \right)^2 \quad (10)$$

Where: CHF = Critical heat flux [kW/m^2]
TRP = Thermal response parameter [kW·s$^{1/2}$/m^2]
$\dot{q}_e^{"}$ = External heat flux [kW/m2]

$$TRP = \Delta T_{ign} \sqrt{k \cdot \rho \cdot c_P \cdot \frac{\pi}{4}} \quad (11)$$

Where: ΔT_{ign} = Difference between ambient and ignition temperature [K]
c_p = Material specific heat [kJ/g·K]
k = Material thermal conductivity [kW/m·K]
ρ = density of material [g/m^3]

4.2.3 Growth phase

Multiple parameters affect the growth rate of the fire. More precise calculations can be done, when the materials of burning items, their location, space geometry and ventilation factors are known. Such detailed information will not be available for this tool, thus a more general concept of fire growth is assessed.

A generally accepted method to describe the growth of most fires, is the so called t^2 fire, where HRR grows exponentially as a function of time. HRR of t^2 fire can be calculated as shown in equation 12. Parameter α is selected from Table 5 based on geometry and contents within the compartment. Determining fire growth rate as t^2 fire using parameter α is a practical engineering assumption. [32-34].

$$\dot{Q} = \alpha (t - t_{inc})^2 \quad (12)$$

Where: $\dot{Q}$ = Heat release rate [kW]
α = Fire growth coefficient [kW/s^2]
t = Time from ignition [s]

Table 5. Parameters used for "tsquared fires", reproduced from [33].

Description	Typical scenario	α [kW/s^2]
SLOW	Densely packed paper products[a]	0.00293
MEDIUM	Traditional mattress/boxspring[a] Traditional armchair	0.01172
FAST	PU Mattress (horizontal)[a] PE pallets, stacked 1m high	0.0469
ULTRAFAST	High rack storage PE rigid foam stacked 5m high	0.1876

[a]National Fire Protection Association (2010) [34].

4.2.4 Flashover prediction

A flashover can be defined as: "*The rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure.*" [35]. The flashover is an important transitional period, as it is often considered as a state, where the enclosure is completely untenable, and fire cannot be suppressed without proficient fire brigade. Only a small portion of fires develop into flashover. For a flashover to occur, a sufficient amount of fuel and oxygen must be present. Whether a flashover occurs depends also on compartment geometry and thermal properties of the walls and other materials present. Usually automatic or manual extinguishing systems can control the fire sufficiently enough to prevent the growth into flashover, or fire becomes oxygen limited before flashover, even if enough fuel would be present. [36] The rest of this subchapter discusses a case, where conditions enable fire growth to flashover.

In light of this thesis, whether flashover can occur or not, and if it can, the time to reach it are of interest.

The occurrence of flashover is conditional to ventilation conditions. After flashover, fire reaches a fully-grown state. As fully grown, compartment fire is usually oxygen limited. Generally, it is assumed that in the case of compartment fire, oxygen is supplied through a door or a window. Windows are assumed to break when fire nears flashover. Air flow through an opening can be approximated with equation 13. [37] This approximation is used in the following methods to approximate the HRR required for flashover.

$$\dot{m}_a = 0.5 A_o \sqrt{H_o} \tag{13}$$

Where: $\dot{m}_a$ = Air mass flow into the compartment [kg/s]
A_o = Area of opening [m2]
H_o = Height of opening [m]

Thomas [38] presented a method to evaluate the required HRR to reach flashover within the compartment. The method is based on energy balance in the upper gas layer in compartment fire. Based on experimental data, Thomas selected the temperature of 577 °C as a criterion for flashover. Equation 14 was derived, which can be used to approximate required HRR for flashover.

$$\dot{Q}_F = 7.8 A_T + 378 A_o \sqrt{H_o} \tag{14}$$

Where: $\dot{Q}_F$ = Heat release rate required for flashover
A_T= Total surface area of compartment

Babrauskas [39] presented a similar method, where the temperature of 600 °C at the upper gas layer was used for flashover criterion. Babrauskas noticed that the relation between HRR required for flashover and stochiometric HRR exists. Stochiometric HRR describes the maximum amount of fuel that can be theoretically burned with a given air flow. Most fuels release heat for about 3000 kJ for burnt kilogram of air. As this can be taken as a constant, the maximum HRR with given ventilation conditions can be approximated with equation 15.

$$\dot{Q}_{stoich} = 1500 A_o \sqrt{H_o} \tag{15}$$

Where: $\dot{Q}_{stoich}$ = Stochiometric heat release rate [kW]

It was noticed that $\dot{Q}_F$ varies between $0.4\dot{Q}_{stoich}$ and $0.7\dot{Q}_{stoicha}$. Best overall fit to original data was obtained with $0.5\dot{Q}_{stoich}$. From this realization equation 16 was derived.

$$\dot{Q}_F = 750 A_o \sqrt{H_o} \tag{16}$$

McCafferey et al. [40] presented another alternative method for approximating HRR required for flashover. This method uses upper gas layer temperature of 522 °C as a flashover criterion. Equation 17 is used to approximate the HRR required for flashover.

$$\dot{Q}_F = 610 h_k A_T A_o \sqrt{H_o} \tag{17}$$

Where: h_k = Effective heat transfer coefficient [kW/m^{2}K]

Poon [41] compared the above-mentioned methods for approximating the HRR required for flashover with different compartment and ventilation parameters. It was found that the method of McCaffrey et al. was the most conservative, giving the smallest HRRs for flashover. Babrauskas' method gave the highest predictions. Poon also compared these calculations with the results obtained from CFAST zone fire model. Thomas' method was in best agreement with the CFAST results. As a result, the method of Thomas was selected to be used in the model.

4.2.5 Fully grown phase

At fully grown phase, maximum HRR will be reached. The power of the Maximum HRR depends on available fuel, ventilation and compartment geometry. The contribution of the compartments' fire load to fire development can be presented in the form kW/m^2, where the amount of HRR [kW] is obtained from statistics. This is a typical way to assess the fire load within a compartment, when more detailed information is not available. If the amount of combustible materials and its properties are known, a theoretical maximum HRR for oxygen-controlled and fuel-surface-controlled fires can be calculated more accurately for a given application. Often fire becomes oxygen-controlled rather than fuel-surface-controlled, for which the method presented above applies to.

The theoretic maximum oxygen controlled HRR was previously presented as $\dot{Q}_{stoich}$, but in reality, combustion is never complete. Equation 18 takes this into account with the combustion efficiency factor, which is the relation between effective and complete combustion [31]. The value for combustion efficiency can be assumed to lay between 0,70 – 0,85 [42].

$$\dot{Q}^{(v)}_{max} = 1500 \cdot \chi \cdot A_o \sqrt{H_o} \tag{18}$$

Where: χ = Combustion efficiency factor

4.2.6 Decay phase

If no automatic or manual suppressing actions are taken, the fire will start to decay when enough fuel has been burned. Decaying of the fire starts when 70 % - 80 % of the fuel load have been burned [20,43]. The decaying phase is exponential with a long tail. The time for the fire to decay is solved from equation 19. The heat release rate during decay phase is presented in equation 20. [31].

$$\int_0^{t_{inc}} \dot{Q}_{inc} \frac{t}{t_{inc}} dt + \int_{t_{inc}}^{t_g} \dot{Q}_{inc} t_{inc} + \alpha (t - t_{inc})^2 dt + \int_{t_g}^{t_d} \dot{Q}_{max} dt = \gamma \cdot q_{total} \tag{19}$$

Where: $\dot{Q}_{inc}$ = Required heat release rate for sustained burning
t_d = Decay start time
t_g = Growth end time
q_{total} = Total fire load
γ = Percentage of consumed fire load before decay phase

Decay scaling parameter adjusts the shape and length of the HRR curve. It is scaled so that the remaining fuel load is consumed during the decay phase.

$$\dot{Q}_{max} \cdot e^{\frac{t-td}{\tau}} \tag{20}$$

Where: τ = Decay scaling parameter

4.2.7 Effect of sprinklers

Sprinklers are dimensioned so that they are able to cut off growth of the HRR and turn it into the decay phase. A traditional empirical model for sprinklers' effects on HRR is presented in equation 21. This traditional model turns the HRR into decay immediately when the sprinklers are activated. A more realistic model, which is more in line with the experiments, is presented in equation 22. This model allows the HRR to grow, but in a slower phase, until it starts to decay. [21]. The latter alternative was chosen to be used in the model due to more conservative results and compliance with the experiments.

$$\dot{Q}_{spr}(t) = \dot{Q}(t_{act}) \cdot e^{-k \cdot (t - t_{act})} \tag{21}$$

Where: $\dot{Q}_{spr}$ = Heat release rate when sprinklers are activated
k = Constant that depends on water mass flux
t_{act} = Time of sprinkler activation

$$\dot{Q}_{spr}(t) = \dot{Q}(t) \cdot e^{-k \cdot (t - t_{act})} \tag{22}$$

It should be noted, that water mist systems have largely replaced sprinkler systems onboard cruise ships. However, there are no proven formulae to model the water mist suppression effect on HRR [21], thus sprinklers are used in the model.

Sprinklers are heat-activated, and their activation can be modelled as a heat detector. Heating of a sensor can be described with equation 23 [21]. A time constant τ is obtained from the equation 24 [21].

$$\frac{dT_d}{dt} = \frac{1}{\tau}(T_g - T_d) \tag{23}$$

Where: T_d = Sensor temperature [°C]
T_g = Hot gas and flame temperature [°C]
τ = Time constant [s]

$$\tau = \frac{RTI}{\sqrt{u}} \tag{24}$$

Where: RTI = Response-time index of the sensor [$m^{1/2}s^{1/2}$]
u = Flow velocity of the hot gases [m/s]

Alpert [44] developed a method for assessing hot gas temperatures and flow velocities, specifically for modelling detector activation. The following correlations are used:

$$T_g - T_\infty = \frac{16.9 \cdot \dot{Q}^{2/3}}{H^{5/3}}, r < 0.18H \tag{25}$$

Where: T_∞ = Ambient temperature [°C]
H = Height from fire base to ceiling [m]
r = Radial distance from fire center to detector [m]

$$T_g - T_\infty = \frac{5.38 \cdot (\dot{Q} / r)^{2/3}}{H}, r \geq 0.18H \tag{26}$$

$$u = 0.96 \cdot \left(\frac{\dot{Q}}{H}\right)^{1/3}, r < 0.15H \tag{27}$$

$$u = \frac{0.195 \cdot \dot{Q}^{1/3} \cdot H^{1/2}}{r^{5/6}}, r \geq 0.15H \tag{28}$$

4.2.8 Effect of the ship's fire brigade

Here the assumption is made, that ship fire brigade reacts to the fire alarm, assembles at the nearest fire station, and heads to the fire location. Success of fire extinguishing by ships' fire brigade depends on multiple parameters, of which the main three are; size of the fire, professional ability and strength of the fire brigade and the accessibility of the fire at its location. Now, in light of this thesis, the accessibility of the fire cannot be taken into account as a variable, as the specific compartment layouts or objects within the compartments are not known. Thus, only the size of the fire at the time of intervention and professional ability and strength of the fire brigade are taken into account.

McDaniel [45] did success/failure probability distributions based on flame/heat area of the fire for individual persons and fire departments with different strength levels. Hakkarainen et al. [21] converted the distributions into SI units. The converted curves are presented in Figure 4. Themelis et al. [23] utilized the same curves in their research for the FIREPROOF project. To model a ships' fire brigade, a 30 % decrease in the probability of success was used in the project FIREPROOF in order to take into account the lesser training of the fire-fighting team onboard a ship and the complexity of the enclosure.

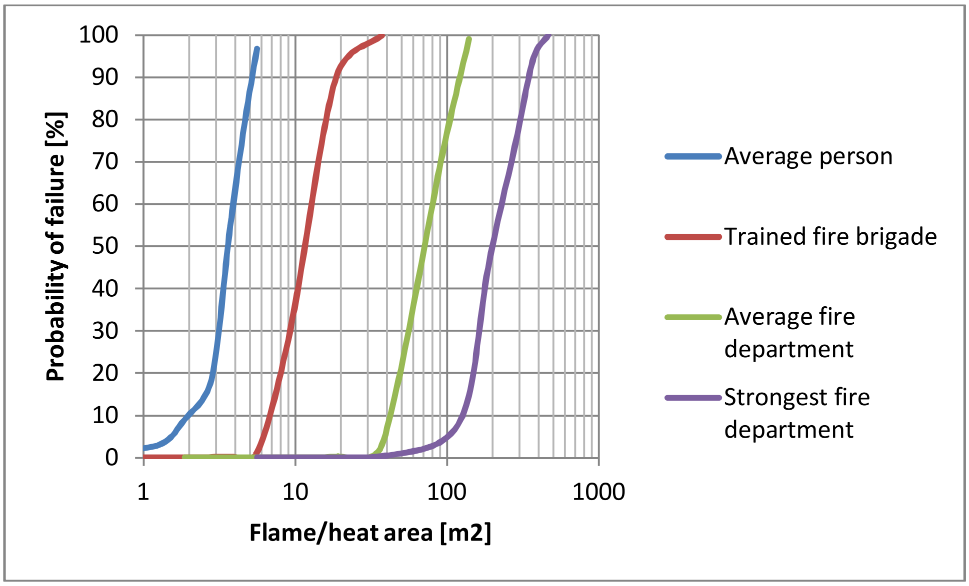

Figure 4. NFPA firefighting failure curves, reproduced from [21].

Themilis et al. [23] used the formulation by Heskestad [46] to calculate the flame/heat area. The equation used is presented in equation 29. It was noted, that fires in compartments could be treated as pool fires, which equation 29 models, with suitable L/D variations. Heskestads' equation relates to outside pool fires and long, deep storage spaces [46]. Thus, the applicability to compartment fires is questionable. In compartment fires the heat radiation from the ceiling to the floor and to the surrounding objects accelerates the fire spread, which then correlates to the accelerated flame/heat area spread. As no better way of determining flame/heat area for compartment fires were found, the above-described method will be used.

$$L = -0.02 \cdot D + 0.235\dot{Q}^{2/5} \tag{29}$$

Where: L = Height of pool fire [m]
D = Diameter of pool fire [m]

4.3 Fire spread

Fire spread requires insulation failure to occur between an initial compartment and an adjacent compartment. In SOLAS Chapter II-2, Reg 9 boundary insulations are specified for every space combination onboard a ship. Each insulation class is tested using the SOLAS standard time-temperature curve. Themelis [31] stated that insulation failure could be assessed by comparing the upper layer gas temperature against the SOLAS standard curve. A similar approach was presented by Guarin [24].

In Guarin's method the correlation between the energy released by the fire and the temperature is utilized. The T·t product of the standard fire is compared to T·t product of the design fire. If A60 boundary is in question, it is assumed that the cold side ΔT is 140 °C after 60 minutes of exposure. Now T·t product of standard time-temperature curve is taken from the time of 60 minutes. When the upper gas layer temperature of the design fire is known as a function of time, the time step, when T·t product of the design fire equals to that of the standard fires at time of 60 min can be determined. At this time, the cold side ΔT can be assumed to be 140 °C.

Walton and Thomas [37] presented a model for approximating the upper layer gas temperature. The model is presented in equation 30.

$$T_g = T_\infty + 6.85\left(\frac{\dot{Q}^2}{A_o\sqrt{H_o}h_k A_T}\right)^{1/3} \tag{30}$$

Where: T_g = Upper layer gas temperature [K]

4.4 Evacuation from initial space

Evacuation from initial space addresses the evacuation from the space of the fire ignition. It is assumed, that the evacuation starts immediately, when the fire ignition is observed. Thus, it is assumed that the fire has not spread from the space of ignition to adjacent spaces, before the space of ignition has been evacuated. Based on these assumptions, evacuees are assumed to be safe, when they exit the space of ignition.

A strategy for the evacuation of a single space can be described as protect-in-place or relocation. In the protect-in-place strategy, adequate fire protection on site is provided to enable the evacuees to stay even in the space of ignition or to escape to adjacent spaces. The protect-in-place strategy is used in complex facilities, especially, when the moving of evacuees is limited for some reason, e.g., in hospitals, surgery facilities, correctional occupancies etc. [47].

In the relocation strategy, the evacuees are evacuated to adjacent spaces, that provide structural fire protection or enough distance to the place of ignition. This strategy is typical for high-rise buildings, where the evacuees are evacuated to the lower floors. [47].

Today, a usual way of assessing the evacuation time of a single space is to conduct agent-based egress simulations. This is the usual way of deriving the required safe egress time (RSET) for an FSA analysis. The available safe egress time (ASET) is then obtained with fire simulations. Agent-based egress simulations require a specific software, which makes the use of such simulations in this model too difficult.

A simpler and less accurate way of assessing the evacuation of a single space, or a larger complex, is the use of hydraulic calculation model. Several hydraulic models exist, and due to simplicity, multiple limitations are present in all of them. Hydraulic models generally calculate as a function of a time, the flow of persons from a component of an evacuation route to the next component. [48].

The method presented in [48] includes the steps explained below, here the only steps needed for calculation of egress time of a single space, are explained. In the method, advancement in each component in the egress route are calculated separately. The components include doorways, corridors, stairs, etc. The method can be used to simulate evacuation of a whole building or another complex system, but it is applicable to a single space as well.

For the calculation, the effective width of the evacuation route component is needed. The effective width is the clear width of the egress component in question. In [48], multiple examples of effective width calculations are presented. Here it is assumed that in the evacuation from the initial space, the doorway is the only egress component. The effective width of a doorway is the actual passage width of the doorway, when the door is open. Thus, the dimension might not be from frame to frame, if the door does not fold far enough.

The walking speed of the evacuees, *S,* is also needed. Based on previous research, it is observed that the walking speed in an evacuation scenario depends, among physical properties of the evacuees, on the density of the population in the space to be evacuated. The walking speed is obtained with equation 31. The speed of an evacuation is presented in Figure 5 as a function of density.

$$S = k - akD \tag{31}$$

Where: D = Population density [persons/m^2]
a = constant, 0,266
k = constant for doorway, 1.40

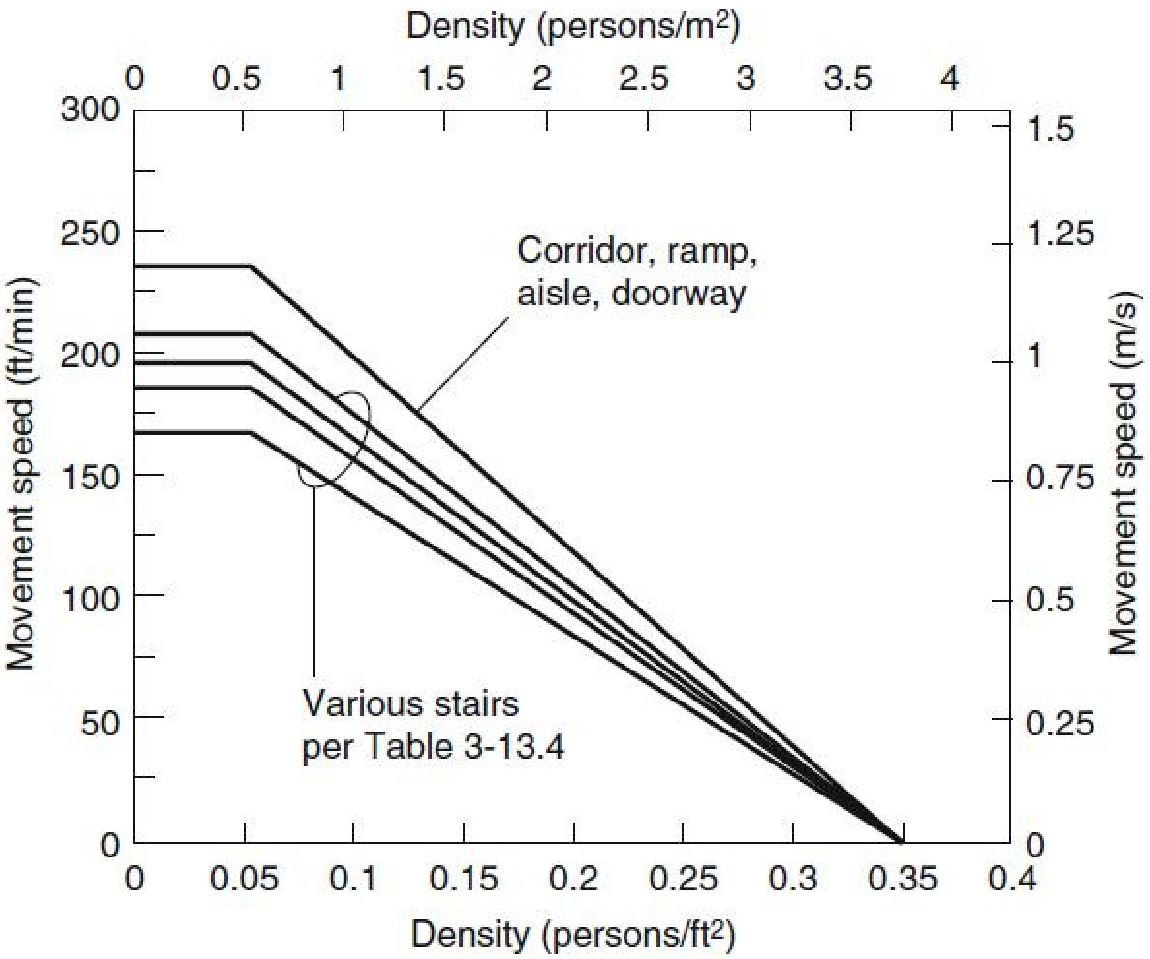

Figure 5. Evacuation speed as a function density [48]**.**

The next step is the calculation of specific flow, F_S. Specific flow is the flow of the evacuees after the specific evacuation component in the calculation. The specific flow is determined as presented in equation 32.

$$F_S = SD \tag{32}$$

Based on the specific flow, the calculated flow, F_c, is calculated. The calculated flow is the flow of persons through specific evacuation components. The calculated flow is obtained as presented in equation 33.

$$F_c = F_s W_e \tag{33}$$

Where: W_e = Effective width [m]

Time of passage t_p of a specific evacuation component is then calculated, as presented in equation 34. This is the evacuation time in case of single space evacuation calculation.

$$t_p = \frac{P}{F_c} \tag{34}$$

All steps can be integrated into one formula, which is presented in equation 35.

$$t_p = \frac{P}{(1-aD)kDW_e} \tag{35}$$

4.5 Ship-scale evacuation

IMO MSC.1/Circ 1533 - Revised guidelines on evacuation analysis for new and existing passenger ships [49], outlines ship-scale evacuation. Ship-scale evacuation is divided in two parts; evacuation to assembly stations and evacuation from assembly stations to lifeboats or to embarkation. A minimum of four cases are required to be analyzed; primary and secondary cases, of which both day and night cases are analyzed. The stages of evacuation are divided in four parts; reaction *(R)*, travel *(T)*, embarkation *(E)* and launching *(L)*. After all individual components are calculated, the overall evacuation time is calculated using the equation 36. As can be seen from the equation, evacuation to and from assembly station to lifeboats is assumed to overlap with one-third of the $E+L$ time. A safety factor of 1.25 is required for reaction and travel time.

$$1.25(R+T) + 2/3(E+L) \leq n \tag{36}$$

Where: n = 80 min for passenger ships with more than 3 main vertical zones
$(E+L) \leq 30$ min

In [49], two methods are presented for evacuation analysis; simplified and advanced. The simplified method utilizes a basic hydraulic evacuation model, while the advanced method allows the use of modern evacuation simulation software, where, in most cases, each agent is treated as an individual. Even though the trend has been more towards the use of modern simulation software, hydraulic models have their place in initial and comparative estimates [12].

5 Model development

In this chapter, development of the model for assessing holistic fire safety onboard a cruise ship is explained. Firstly, it should be addressed that this model is meant to be used in the concept phase of a cruise ship design, as well as for comparing fire safety levels of different cruise ships. The use in concept phase sets some limitations and requirements. Limitations arise from the quality of available data and the main requirement is that the model should be fast and easy to use. In the concept phase changes in design occur often and quickly. If an excessive amount of labor is needed to get results from the model, it will not be used. So, the focus on development of this model is in the ease of use, and in some cases with the cost of accuracy. Another point is that, as the model is meant - at least in this phase - for comparative use, assessing the actual fire safety level is not of highest priority. Instead, in this phase, it is enough that in most cases a change in the parameters changes the results in a reasonable direction and with reasonable magnitude.

The fire risk index approach was selected to be used. The FRI method was previously presented in this paper. Below, in Figure 6, the block diagram of function of the model is presented. Two workbooks are used, PFS and Risk Model (RM). The general functioning of the model and its parts are presented below. More detailed descriptions of the modules and the mathematical solutions are presented later in this chapter. Now, the first role of the PFS is explained and RM is assessed afterwards.

The PFS simulates design fires. In each simulation, an HRR curve is created. Variables, like the floor area of the compartment and the fire growth rate, which are used for the design fire, are randomly sampled separately for each simulation from pre-determined probability distributions. From each simulation, the floor area of the simulated space, and whether flashover occurred and/or whether boundary penetrations were experienced, are recorded. As a result, a database is created. Fire categories are assigned based on SOLAS space categories. Overlap in fire-related parameters led to eight fire categories, which are used for all 14 SOLAS space categories. A separate database is created for each fire category.

Next, the use of the RM is explained. All eight fire-category specific databases are imported to the RM. Next, ship specific space attributes are imported from NAPA. With these parameters, the RM calculates everything else. The formation of the final FRI is discussed next. As mentioned earlier, the RM consists of three modules; fire safety, evacuation and resilience. Each module is explained separately below. From each module a score is obtained. The score can vary between 0 and 1. The higher the score, the better. The final FRI is then obtained by multiplying the scores with weight values. At the time of writing this thesis, each module is considered as equally important, thus the weight value of each module is 1/3. This means that the final FRI can vary between 0 and 1.

Fire module

In the fire module, a space specific sub-fire-risk-index is calculated for every space onboard. The index consists of probabilities of boundary penetrations and flashovers, and in some spaces, from the time it takes to evacuate a single space under evaluation. The ignition frequency of the space is calculated as presented in equation 7. The probability of flashover and boundary penetrations are obtained as presented in section 5.4. If a SOLAS category 8 space, i.e. a public space, is in question, then also the evacuation time of the space in question, calculated as presented in section 4.4, is taken into account in the space specific sub-fire-risk-index. The evacuation time of the space is scored based on the time it takes to empty the room. The individual space sub-fire-risk-index is then the sum of flashover and boundary penetrations probabilities and the initial space evacuation score. The combined spaces' sub-fire-risk-index is then obtained by summing the scores of all spaces onboard, and then by dividing the sum with a reference value, which sets the score between 0 and 1.

Evacuation module

In the evacuation module, the ship-scale evacuation is assessed. Now, it should be mentioned, that the evacuation module was left unfinished, as a reliable and suitable way of assessing embarkation was not found. Evacuation to assembly stations is calculated as presented in section 5.3.1 and ship-scale evacuation is calculated as presented in section 5.3.2. The time results obtained from these calculations are then summed and divided by a reference time. The result is the ship-scale evacuation sub-index, which varies between 0 and 1.

Resilience module

The resilience module assesses the ships' capability to perform its duty as the best lifeboat after a large, 1 - 2 MVZ fire. The items, which are evaluated, were selected based on a questionnaire, explained in section 5.2. The weight values for the items were obtained using the Analytical Hierarchy Process, described in section 5.2 as well. A set of measurable and quantitative parameters were selected based on the expert judgement of Meyer Turku, to represent each item, which was selected as a measurement criterion from the questionnaire. In the resilience module, the ships' features are compared to the parameters of the particular item, and a score is obtained. Each item can obtain a score between 0 and 1. The score is then multiplied by the weight value of the item, presented in Table 7. As a result, the maximum score from the resilience module is 1.

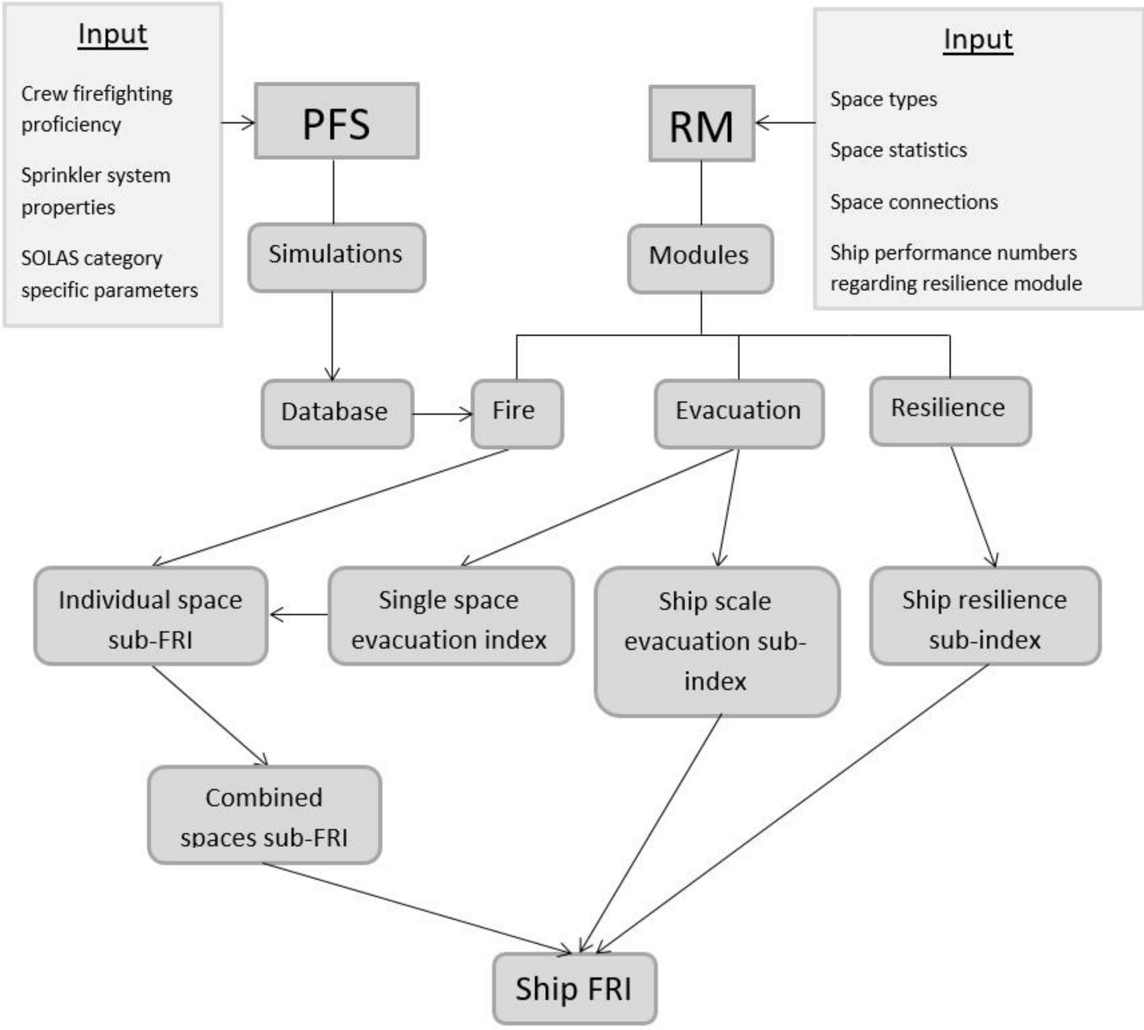

Figure 6. FRI block diagram.

5.1 Input data

NAPA allows straightforward data exportation from the ship database with custom macros to .csv format. So, it was decided, that input for the model would be exported from NAPA to as a large extent as possible.

NAPA has an insulation manager, which automatically generates the required insulations for bulkheads and decks, based on SOLAS' categories. When the insulation manager is used, the accuracy of the ship space or volume model is crucial. If modelling errors occur, incorrect insulations can be assigned. It was decided, that the easiest way to export the required data was to use the insulation manager with added custom macros. Information from the insulation manager, i.e. the space connections and insulations, are needed further on. Additional macros were added to the insulation manager, which extracts other needed data. This way, one manager tool can be used for all purposes of the developed model. The exported data will be addressed more closely below, with parts of the model, where certain data is used.

As deck numbers are not available in NAPA, a suitable formulation had to be configured into RM. From NAPA, minimum and maximum Z coordinates of each space are obtained, and based on these, the deck number can be determined. In the RM, the user must manually feed all deck heights and corresponding deck numbers. Then, based on the comparison between minimum and maximum Z coordinates and deck heights, the RM determines the deck number.

5.2 Resilience module

The idea behind the resilience module is to include the ships' ability to function after a large, 1 - 2 MVZ fire, into the model. In the model, the resilience module includes the attributes and their weightings. The user of the model then needs to assign ship specific scores for each attribute. In order to enable scoring of the attributes for a specific ship, a scoring table will be formed. In the table, the scores are obtained by using physical measurements or other quantitative measures. Quantitative measures are used to avoid biased and uninformed scores by the users. As an example, the availability of electricity after a 1 - 2 MVZ fire could be scored based on the longitudinal and vertical distance between the main engine rooms and the emergency generator, if the cabling is fire-protected, and by the number of main engine rooms and if the main engine rooms are located within the same MVZ.

Questionnaire

As no meaningful way to quantify this type of resilience based on the NAPA input was available, it was decided, that the attributes and their weight values would be obtained based on a two-part questionnaire and the utilization of AHP.

In the first part of the questionnaire, the recipients were asked to list in rank order the ten most important items or features that should remain functional after a large 1 - 2 MVZ fire, where 1 being the most important and 10 being the least important. The answer sheet is presented in Appendix 1. The answers from the first part were analyzed and the 7 most often answered and highly ranked items or features were selected as attributes for the resilience module. As no answer alternatives were provided in the questionnaire, the same items and features were mentioned in a slightly different manner multiple times. Thus, in the analyzing process, based on the answers and explanations, the same answers that were written in a slightly different manner were combined. The selected attributes are presented in rank order in Table 6. All of the selected attributes were answered by at least by 50 % of the questionnaire attendees. Ranking of the attributes was performed by reversing the rank order numbers assigned by the questionnaire attendees and by summing the points obtained by each answer. Thus, the attribute that was seen as most important by the questionnaire attendees gained 10 points and the least important gained 1 point.

Table 6. Selected attributes for resilience module.

1	Emergency Power
2	External Communications
3	Fire Fighting Systems
4	Internal Communications
5	Availability of LSA
6	Crew Emergency education/Skills
7	Fire main availability/capacity

In the second part of the questionnaire, the recipients were asked to compare the selected attributes against each other and to assign importance values for one over the other by using the scale in Table 1. A template was formed, which included all 21 comparisons, which was sent to the same professionals that answered in the first part. The template is presented in Appendix 2.

The results of the second part of the questionnaire were analyzed using an Excel template [50]. Nine professionals answered the second part of the questionnaire. Consensus of the pairwise comparisons between the participants was 66,8 %, which is scaled as "moderate" by the template. The mean relative error of the final eigenvector is 25,9 %. Given the complexity of the comparisons, the result can be thought to be reasonable. Differences in the pairwise comparisons highlight the need for multiple participants in a questionnaire like this.

The final weight values of the attributes are presented in Table 7. Interestingly, the final weight values were not in line with the results of the first part of the questionnaire. In the first part of the questionnaire the participants had to come up with the items and features without any proposed alternatives. In the second part comparisons between the selected alternatives were provided. This most likely led to more thoroughly thought answers and comparisons. Also, the items or features that an individual participant did not answer in the first round were presented in the comparisons of the second round. Based on the valuations it was clear, that many participants valued items and features highly, even though they did not come up with that specific item/feature in their own first round answer. This induces differences in the final preferences.

Table 7. Attribute weight values.

1	Emergency Power	0,179
2	External Communications	0,072
3	Fire Fighting Systems	0,224
4	Internal Communications	0,257
5	Availability of LSA	0,100
6	Crew Emergency Education/Skills	0,052
7	Fire Main Availability/Capacity	0,115

Consistency of the pairwise comparisons by an individual participant describes how logically the individual has valued different comparisons. A limiting value of 10 % was proposed by Saaty [18] to deem the comparison as successful. Elsewhere, in the context of multiple participants in the same AHP evaluation, the limiting factor of 10 % is criticized to be unrealistic [50].

Consistency ratios (CR) of matrixes produced by individual participants varied between 5 - 56 %, the average CR was 19,4 %. Only two matrixes resulted in a lower than 10 % CR. Thus, another refinement round should be performed for the rest of the matrixes by the participants.

Ship evaluation against selected attributes

A quantitative way of evaluating the ship regarding the selected attributes, which are presented in Table 6, was developed. A set of multiple parameters of ship features were selected to represent each attribute shown in Table 6. A group of professionals from different design departments at Meyer Turku developed the sets of parameters, to ensure as reliable and realistic assessments, as possible. Depending on the nature of the parameters, simple "yes" or "no" answers are used to evaluate the performance of the ship regarding the parameter, or a linear scale is used. If a linear scale is used, minimum and maximum values are selected based on statistics of the feature in question. A weight value was also assigned for each parameter so that a score regarding for one attribute from Table 6 can vary between 0 and 1.

This score is then multiplied with the weight value of the attribute in question. As a result, the score from the resilience module can vary between 0 and 1.

5.3 Evacuation module

The evacuation module is divided in two sections; evacuation from initial space and ship-scale evacuation. Evacuation from initial space is meant to assign each space in the ship an evacuation performance sub-index, which is then used together with the results from the fire module, in order to derive a space-specific FRI.

Ship-scale evacuation forms the evacuation sub-index of the ship. In ship-scale evacuation, day- and night-time cases will be taken into account. Due to time constraints, development of the ship-scale evacuation module was excluded from the scope of this thesis. A ship-scale evacuation module will be developed in the future. Some initial considerations about ship-scale evacuation were addressed and are explained below.

5.3.1 Evacuation from initial space

The evacuation time from a cabin or from another similar small space, depends mainly on the reaction time of the individuals in the space. The length of the evacuation route and the door sizes are irrelevant in these cases. Human life can be assumed to be endangered in a fire in the above-described small spaces in the following situations; the persons in the spaces are sleeping, sprinklers do not activate and the fire is able to develop freely, or smoldering combustion produces enough toxic gases to cause a threat for health. As evacuation in these cases is not the criteria to determine whether the persons survive, such spaces are not taken into account in evacuation-from-initial-spaces part of the module.

Among the most relevant spaces to be considered in this section are large public spaces, from where a big number of people must be evacuated in case of fire.

Due to the above-mentioned reasons, in the model, the evacuation time in the initial space is taken into account only in calculation of space-specific FRI sub-indexes of public spaces.

The hydraulic model, which was presented previously, is utilized. The needed effective width of the doorway and population density is obtained from the FSS code [6]. In the FSS code, the number of persons P in public spaces is calculated as shown in equation 37. The effective width of the doorway is 900 mm at minimum, if more than 90 persons can be assumed to facilitate the space, then the effective width is calculated using equation 38.

$$P = \frac{A}{2} \cdot 0.75 \tag{37}$$

$$W_e = 0.9 + (P - 90) \cdot 0.01 \tag{38}$$

As the density of persons stays constant, also the specific flow stays constant. This results in a situation, where the maximum evacuation time is 211.6 seconds using the hydraulic model. This time is achieved with a floor area of 240 m^2. When the floor area decreases from this, the evacuation time gradually closes to zero. If a larger floor area is calculated, the evacuation time will always stay constant. This is not the most realistic scenario, but it is quite well in line with a confidential study that Meyer Turku commissioned VTT to perform [51]. According to the study, in most fire cases, large public spaces were evacuated in approximately three minutes.

5.3.2 Ship-scale evacuation

Here it should be noted, that the rules for evacuation always guide the design of the ship. When the stairs, evacuation routes and doorways are dimensioned according to the requirements, ship-scale evacuation performance is, based on the experience of Meyer Turku, within acceptable time required by the prescriptive rules. If the first evacuation simulations are not successful, the most critical items or locations are studied and the required changes into the design are implemented to reach the required evacuation time. Due to the above-mentioned matters, ship-scale evacuation performance is assumed to vary between different ships within a normal scale of ship evacuation times.
Developing a reliable and justified way of assessing embarkation from the assembly stations to the lifeboats and MES, turned out to be rather time-consuming. Due to the above-mentioned reason and to the already large scope of the thesis, developing an embarkation model was left to be done in future work.

A method for assessing the first part of the evacuation; passenger movement to assembly stations, is presented below.

<u>*Evacuation to assembly stations*</u>

The approach presented here is based on the expert opinion and experience of Meyer Turku and Tim Meyer-König from Traffgo-HT, who have been involved in the development of IMO evacuation analysis guidelines.

In typical evacuation simulations, a large number of simulations are run. Due to probabilistic pedestrian characteristics that are used in the simulations, the simulation results vary. From all of the simulations, the 95-percentile result is used as a final result. This means the value, of which 95 % of the simulations were faster, and of which 5 % were slower.

Based on Meyer Turku's and Traffgo-HT's experience, it has been observed, that when enough evacuation simulations are conducted, the longest evacuation times arise from situations, where the person with the slowest possible reaction time and walking speed, according to the IMO criterion, is situated in the most distant location from the assembly station. The longest times usually represent the 95-percentile result quite well. Based on this realization, an Excel spreadsheet in RM was created, which, in a day case, automatically recognizes the most distant space within the same MVZ from the assembly station and calculates XYZ distances from that space to the assembly station. In a night case the procedure is the same, except the most distant cabin is used for the XYZ distance calculations. Within the spreadsheet these distances are then multiplied with the walking speed in the form of m/s. Walking speeds are obtained from MSC1533 [49]. As a result, durations for each movement are obtained and these are then summed, and the reaction times are added. The result is the evacuation time. This method does not produce a fully realistic evacuation time, which could be thought of as an equivalent observation to the actual evacuation simulation result. However, the method provides a simple and comparable way of assessing evacuation to assembly station.

5.4 Fire module

The fire module consists of two parts; the first part is in the model itself and the second part comes from a specific PFS workbook. Ignition frequencies are calculated in the model and the events after fire ignition are obtained from the PFS input. In practice, a database of fire scenarios is created with PFS for each fire category. From the simulations that form the database, thee floor area and whether flashover and/or boundary penetrations occurred, are recorded. These databases are then imported into the model. Based on the floor area, the SOLAS category and adjacent spaces, the probability of flashover and fire spread to an adjacent space, is obtained from the database. The probability of flashover for a single space is obtained by finding spaces with similar floor areas as the space under the evaluation, from the correct database, and dividing the number of found areas by the number of occurrences of flashovers in the found spaces. The same principle is used for probabilities of boundary penetrations.

Probabilities derived from the database do not include contribution of ignition frequency. Thus, space-specific probability of flashover is obtained with the equation 39 and the probability of fire spread to adjacent spaces with the equation 40. These probabilities are then used to derive the space-specific fire safety sub-index.

$$P(F_i) = \gamma_i \cdot P(F_{di}) \tag{39}$$

Where: $P(F_i)$ = Probability of flashover in space i
γ_i = Probability of ignition of space i
$P(F_{di})$ = Probability of flashover in space i, derived from database

$$P(S_i) = \gamma_i \cdot P(S_{di}) \tag{40}$$

Where: $P(Si)$ = Probability of fire spread from space i
$P(Sdi)$ = Probability of fire spread from space I, derived from database

As calculation of fire scenarios requires deep understanding of the phenomena and calculation process, the division in two parts enables simple and easy use of the model. On the other hand, the division also enables more a complex and accurate fire scenario generation. Implementing all the required formulae and processes into same model, where information from thousands of spaces is imported, proved to be quite challenging. Basically, the idea is that almost anyone can use the model itself if no changes in the fire scenarios are needed. This is the case, e.g., when the layout of the ship is changed, or new spaces are added. If changes to the fire scenarios are needed, then a more fire-inclined person will modify and run the new PFS workbooks.

5.4.1 Fuel load

Fire load density and fire load can be calculated accurately for a given space, when the combustibles within the space are well known. As the model developed in this thesis does not possess such information, simplifications are required.

Like mentioned before, the SOLAS limits the amount of combustible materials used onboard a ship and based on SOLAS' space categories. Thus, the mass per unit area of combustible materials is based on the SOLAS category. The amounts of combustible materials in each SOLAS space category is presented in Table 8.

Table 8. Amounts of combustible materials.

SOLAS category	Definition	Amount of combustible material [kg/m^2]
1	Control station	15
2	Stairway	5
3	Corridors	5
4	Evacuation station and external escape routes	15
5	Open deck spaces	10
6	Accommodation spaces for minor fire risk	15
7	Accommodation spaces for moderate fire risk	35
8	Accommodation spaces for greater fire risk	35
9	Sanitary, and similar spaces	10
10	Tanks, voids and auxiliary machinery spaces having little or no fire risk	5
11	Auxiliary machinery spaces, cargo spaces, cargo and other oil tanks and other similar spaces of moderate fire risk	35
12	Machinery spaces and main galleys	45
13	Storerooms, workshops, pantries, etc.	20
14	Other spaces in which flammable liquids are stowed	45

5.4.2 Ignition frequencies

Previous research on ignition frequencies onboard cruise ships were discussed before in section 4.1. Due to the large database used in the project FIREPROOF, SOLAS category specific ignition frequencies obtained by Themelis and Nikos [23] were chosen to be used in the model. As ignition frequencies are already expressed as $s\text{-}y/m^2$, the ignition frequency for each space is obtained easily by multiplying the floor area of the space with the SOLAS category specific ignition frequency. Besides the floor area and SOLAS category, deck and MVZ - where the space is located - is imported to the model from NAPA.

Ignition frequencies of each space are used later in forming space specific sub-attribute for overall fire safety index. For illustrative and comparisonal purposes, ignition frequencies of each space within same the deck and MVZ are summed and presented in illustrative table with color coding, based on ignition frequency. Example of generated table is presented below Figure 7. Table provides an easy way to observe the ignition frequency distribution and to identify areas with most frequent fire ignitions. It should be noted that in Figure 7, ship is facing left instead of normal direction, right.

		MVZ				
		1	2	3	4	5
Deck	13		0.000377			0.000726
	12		0.004883	0.004109	0.005096	0.004804
	11		0.086408	0.160079	0.165154	0.207922
	10		0.102026	0.07361	0.221112	0.133099
	9		0.126272	0.092905	0.064829	0.07192
	8	0.000309	0.084415	0.104356	0.081193	0.072017
	7		0.084345	0.038108	0.053648	0.070892
	6		0.082659	0.044877	0.070179	0.071908
	5	4.67E-05	0.031513	0.040022	0.108143	0.064411
	4	0.008799	0.001506	0.004481	0.001641	0.003681
	3	0.009772	0.006239	0.002578	0.016542	0.003561
	2	0.008132	0.126518	0.350956	0.127466	0.068281
	1		0.003595	0.666127	0.024415	0.001346

Figure 7. Ignition frequencies per deck/MVZ.

5.4.3 Fire scenarios

As mentioned, the fire scenarios are calculated with PFS. The equations presented in section 4 are used. The constructed PFS model calculates each fire scenario independently. From each simulation, the floor area, whether flashover occurred or not and whether a failure of 15, 30 or 60 minutes rated boundaries were achieved, are recorded. All the aspects presented in section 4 are implemented into the model. Based on variable parameters, each simulation calculates the HRR development with s 20 second time step from 0 to 240 minutes. Variable parameters and their distribution types are presented in Table 9.

Table 9. Variable parameters.

Response-time index, *RTI*	Uniform
Fire growth rate, α	Triangular
Floor area, *a*	Uniform
Fire brigade response time, t_{resp}	Custom
X-distance from fire to detector, *x*	Uniform
Y-distance from fire to detector, *y*	Uniform
Sprinkler activation probability, S_{AP}	Uniform
Fire brigade success probability, FB_{SP}	Uniform

When no more detailed analysis for the fire growth rate in every application is performed, the single or variable fire growth rate is usually used. For the variable fire growth rate, uniform, normal and triangular distributions are the most common, depending on the application. When assigning fire growth rates for SOLAS categories in the model, based on the descriptions of fire growth categories, the most applicable and one higher were selected. One higher was opted to emphasis the worst-case scenario. When assigning the distribution type, it was rationalized, that normal distribution would give too much emphasis on the high end of values, and normal distribution would give too much variation in sampling due to thin ends of the spectrum. Thus, triangular distribution was selected.

The fire brigade response time (t_{resp}) is a custom probability distribution. The distribution describes the time between the fire alarm and the time, when the fire brigade reaches the fire site. Thus, the time includes reaction time, travel to the fire station of the same MVZ, preparation and travel to fire site. The distribution is constructed based on the experience and operational practices of a ship operator; Royal Caribbean Cruise Line [52].

As a single simulation is meant to produce an actual HRR curve and not just probabilities of events, a slightly more complex approach is required for the parameters, which are expressed as probabilities.

Whether the sprinklers activate or not depends on sprinkler reliability level (S_{RL}). As this can change based on the sprinklers used, an easily changeable reliability level was implemented into the model. In the model, the user sets the sprinkler reliability in the form of 0 - 1, usually around 0.96. The variable parameter, sprinkler activation probability (S_{AP}), ranges uniformly between 0 and 1. In the model, sprinklers are activated if $S_{AP} < S_{RL}$.

A similar approach was implemented for the probability that the ships' fire brigade is successful in suppression of the fire. All four fire-area-dependent probability distributions, which were presented in section 4, are implemented to the model. The user needs to select, with which fire brigade proficiency level the ship is equipped with. Then, based on the size of the fire at time of fire brigade intervention, suppression is determined to be either successful or unsuccessful. Again, if the variable parameter fire brigade success probability (FB_{SP}) is greater than the fire area-dependent failure probability obtained from the distribution, the fire brigade is successful.

5.4.3.1 Assumptions in the model

As probability of flashover and boundary failures are selected as the criteria for fire risk sub-index for an individual compartment, determination of these is the main task of the PFS model. In theory, it would be possible to mathematically model a fire model which takes into account all of the affecting factors and their probabilities. This would, however, result in an unnecessarily complex model, that would be almost impossible to modify in the future. Also, available data for some factors is not relevant nor accurate enough to justify direct use in the fire model. To encounter this problem, some assumptions are implemented in the model.

The mathematical model of the sprinkler always leads to fire decay, if the sprinkler is activated. This might not be true in all possible cases but based on literature and the comparative nature of the model, this assumption is accepted.

In the model, if no suppressing actions are taken, fire will always reach flashover if ventilation, fire growth rate, and fuel load within the compartment enable it. The sprinklers' effect on fire development is implemented in the model, as presented earlier in this paper. There is a possible scenario, where the sprinkler activates right before flashover, and as HRR growth is not cut into decay immediately when the sprinklers are activated, flashover could still be reached. This scenario is seen as unrealistic. In reality, the sprinklers' cooling effect would most probably cool the surfaces of the compartment enough to prevent full flashover. Thus, in the model it is assumed, that if the sprinkler is activated before flashover, flashover cannot occur.

Generally, the sprinklers should be activated before the ships' fire brigade arrives to the fire site. However, if the sprinklers do not activate and no manual suppression by on site personnel is attempted, the first suppression attempt is assumed to be performed by the ships' fire brigade. The probability of success of suppression by the ships' fire brigade was dealt with earlier in this thesis. In each simulation case, based on the fire size at the time of arrival and proficiency of the fire brigade and based on probability, the success of suppression is determined. If suppression is determined to be successful, it is assumed, that if the fire brigade reaches the fire site before flashover, it can control the fire and cool the compartment surfaces sufficiently enough so that flashover is prevented.

Fire spread from the compartment where fire has ignited to an adjacent compartment, is assessed only through intact and insulated boundaries. Fire spread through ventilation channels etc. is not considered. It is also assumed that doors are closed. It is recognized that in reality, fire is most likely to spread though doors, which are left open. Another probable spread route is faulty openings and penetrations in boundaries [53].

Fire spreads through boundaries to adjacent spaces, if insulation fails and the temperature on the cold side of the boundary is high enough to ignite an item in the adjacent compartment. In the model, the hot upper layer gas temperature is used to predict fire spread into adjacent compartments. In reality, the fire location plays an important role when the heating of the boundary is assessed in an early phase of the fire. If the fire is located away from the boundaries, until flashover or major fire spread, relevant heating of the boundaries is done mostly by the hot upper layer gases and some radiation, depending on the distance to the boundary. At the beginning of the fire, hot upper layer gases cool quite rapidly when the distance to the fire source lengthens. After the fire has ignited and developed into a flaming phase, local heating is more rapid, if the fire is located near the boundary, due to instant heating caused by more intense radiation. The mathematical model that is used for predicting hot upper layer gas temperature assumes that the fire is located at the center of the compartment. The model gives only one temperature for the hot upper layer gases. This temperature is assumed to be an average hot upper layer gas temperature. In the model, fire location is not varied in any way. If more detailed and realistic risk figures were to be sought after, fire location should be a variable in the model. However, as the model is of comparative nature, the current method is justified and produces comparable results.

In the PFS model, it is also assumed, that if the ships' fire brigade reaches the fire site before fire spread into adjacent spaces, and if suppression is determined to be successful, the fire will not spread even if flashover has occurred or will occur. This assumption is based on boundary cooling and moving ignitable items in the adjacent compartments further from the boundary between the fire compartment and the adjacent compartment. This assumption might not be true for all possible scenarios, but based on Meyer Turku's expert opinion, this is a justifiable assumption and a most probable outcome.

5.4.3.2 Effective heat transfer coefficient

The effective heat transfer coefficient describes heat absorption into the boundaries of the fire enclosure. Methods for calculating h_k are designed for the general building industry. The general procedure for the calculation of h_k value assumes that the value is time dependent. The value is time- and temperature-dependent. General procedure for value calculation produces reasonable results when wall materials are concrete, for example. When the procedure was used for insulated steel boundaries, the results were unrealistic.

As h_k value is needed for hot upper layer temperature calculation, a calibration method was derived. Detailed fire simulations of typical compartment fire within insulated steel boundaries were performed with a computational fluid dynamics (CFD) software; Fire Dynamics

Simulator (FDS). From the simulations, temperatures and the HRR were recorded as a function of time.

Value of h_k was then calibrated to produce the same temperatures in similar fire and compartment dimensions as with equation 17. The value of h_k varied between 0.32 and 0.01. To achieve more realistic results, this procedure should be done for different sizes of compartments with different types of fires. Due to time constraints this will be done in the future. The model is still considered usable due to its comparative nature.

5.4.3.3 Number of simulations in PFS

The number of simulations in PFS needs to be optimized in order to shorten the computational time required for FRI calculation. The use of LHS versus traditional Monte Carlo, decreases the amount of required simulations due to a more even sampling. However, due to multiple random parameters in the model, a considerable amount of simulations for each compartment size is required to achieve consistent probabilities for flashover and boundary failures. With a big enough number of simulations, the model will always produce the same probabilities. If the number of simulations is too small, the calculated probabilities start to vary.

Parameters that depend on SOLAS category are the fire load and the fire growth rate. Some SOLAS categories were estimated to have the same fire load and fire growth rate. This led to eight different PFS workbooks, which must be calculated separately. Fire growth rate within the same SOLAS category spaces is assumed to vary between two consecutive values between SLOW, MEDIUM, FAST and ULTRA FAST. The numerical values were discussed earlier in this thesis. Floor areas of compartments in cruise ships vary roughly between 1 - 3000 m^2. The floor areas of a single SOLAS category typically varies with smaller distribution, thus the simulation of whole 3000 m^2 spectrum is not needed for most SOLAS categories, when the database is constructed.

Besides variations within the SOLAS categories, the firefighting proficiency level of the ship crew ended up being a major consideration when determining the required number of simulations. This the result from a situation, where a weaker fire department cannot suppress a fire, which a stronger fire department might be able to suppress. Thus, if a weaker department is considered, failure is obvious and small number of simulations is enough to determine the probability. With a stronger department, a big number of simulations is required, as the suppression is successful occasionally.

The required number of simulations for each SOLAS category with a specific firefighting proficiency level was determined by selecting a few typical compartment sizes with even distribution from floor area distribution of a given SOLAS category. For each compartment size, initially 20 000 simulations were calculated, and probabilities were recorded. Then, the number of simulations were periodically decreased until variation started to arise and were then compared to the initial probabilities from 20 000 simulations. The selected number of simulations was the number that produce the same probabilities as the initial simulations with a 95 % confidence level.

As the required number of simulations varied within the same SOLAS category, based on compartment size, the largest required number of simulations was initially selected for each SOLAS category. The number of required simulations ended up being too high to enable simulation of one SOLAS category with one PFS spreadsheet, as the Excel row number ended up being the limiting factor. Originally, the required number of simulations was investigated with 1 m^2 variation in floor area. Further analysis was performed to decrease the number of simulations. It was observed, that similar probabilities for a given compartment size were obtained when simulations with a $\pm$ 2.5 m^2 variation in the floor area were taken into account. As a result, the required number of simulations was decreased by 75 % from the initial number. However, the number of rows still ended up being an issue with the better performing firefighting levels. To combat this issue, careful investigation was performed, and distribution of floor area was changed from uniform to custom, where the areas that needed more simulations than others, were weighted. As a result, the number of simulations was decreased substantially, while maintaining an acceptable 95 % confidence level.

It was noticed, that the fire growth rate is the largest SOLAS category specific attribute affecting the required number of simulations. Differences in growth rate between FAST and ULTRA FAST is the largest, when consecutive fire growth rates are compared. This resulted in a need for the biggest number of simulations with SOLAS categories, where the fire growth rate varies between FAST and ULTRA FAST.

The need for the biggest number of simulations is in cases, where the fire growth rate varies between FAST and ULTRA FAST, and the ship is equipped with the most proficient firefighting team. The level of the firefighting proficiency onboard was observed to be the single most affecting factor affecting the required number of simulations. As flashovers and fire spreads are rarer, when a more proficient firefighting team is present, more simulations are required to attain consistent probabilities.

6 Case study

The main purpose of the case study is to verify that the model works in an actual application. Another object is to conduct a rough sensitivity study to ensure that parameter changes affect the results in a correct and predictable way. A modern cruise ferry, hereafter to be called the model ship, was selected for the case study. Main dimensions and general information of the model ship is presented in Table 10. Car decks of the model ship had to be excluded from the study, as the mathematical models in the model are not suitable for as large open spaces as car decks. It should be also noted, that the evacuation module was not used in this case study due to the unfinished ship-scale evacuation part of the module. Evacuation from the initial space was enabled as part of the individual space FRI.

Table 10. Model ship parameters.

Length	218	m
Beam	31,8	m
Passenger capacity	2800	
Crew capacity	200	
Nr. Deck	13	
Nr. MVZ	6	

The study was initiated by extracting the ship data from NAPA to RM. At this point, some minor adjustments, like deleting car decks, had to be done. Based on the imported attributes, the RM successfully calculated all steps, to which information outside NAPA data is not needed.

The next phase was collecting the needed information to run PFS simulations. All together 8 workbooks had to be created. Variables between the workbooks were the fire growth rate and the amount of combustible materials. For the case study, the fire brigade proficiency level *"Average Department"* was chosen. The categories and their variables can be seen in Table 11. The summarized number of simulations, from where the database was created, ended up being 3 557 000, which means that an equal number of rows had to be imported into RM.

Table 11. Fire categories.

Fire category	HRR Growth RATE	Fire load [kg/m^2]
1	MEDIUM - FAST	5
2	MEDIUM - FAST	10
3	MEDIUM - FAST	15
4	MEDIUM - FAST	35
5	FAST - ULTRAFAST	15
6	FAST - ULTRAFAST	35
7	FAST - ULTRAFAST	20
8	FAST - ULTRAFAST	45

After importing the database from PFS simulations, it became clear, that some functions in the RM were too calculation intensive, and the RM slowed down considerably, and the calculation updates took several minutes. This problem in managing the RM was resolved by disabling some calculation sheets. This way the RM can be modified. When the final result is sought after, all calculation sheets are enabled, and the time-consuming calculation is done only once.

Once the probabilities of flashovers and boundary penetrations were calculated for all of the compartments of the ship, the probabilities were analyzed in groups. The groups were assigned according to fire categories, which were developed for PFS simulations. Some similarities among the results were noticed. Flashovers were not experienced in compartments smaller than 25 m^2, also flashovers were not experienced in compartments with greater than a 100 m^2 floor area. Flashover probabilities as a function of floor area of the compartment can be seen in Figure 8.

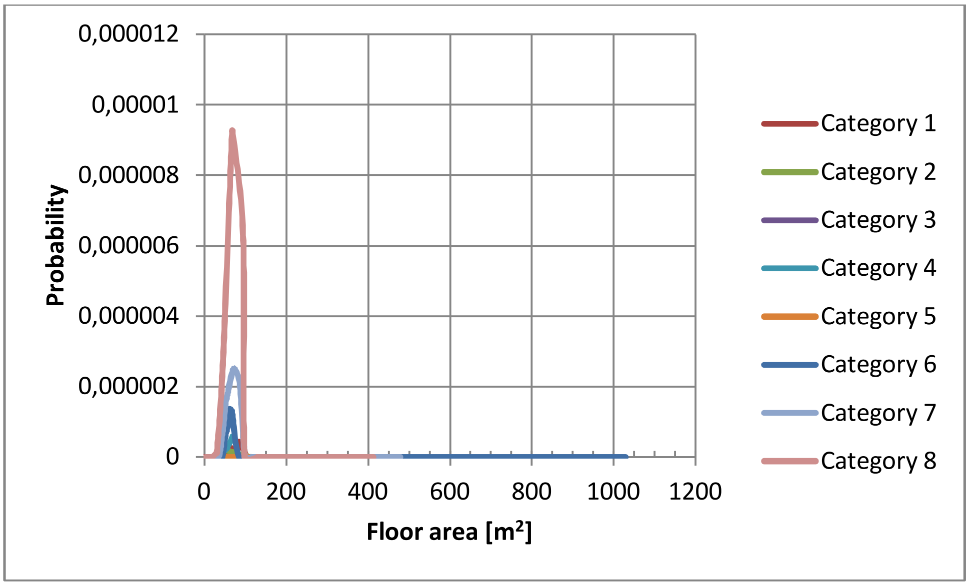

Figure 8. Model ship flashover probability.

In smaller compartments, boundary penetrations started to occur with the same floor areas, as flashovers. However, boundary penetrations occurred also in the largest simulated compartments, except in category 1, where the amount of combustible materials within the compartment was the lowest. Probabilities of boundary penetrations can be seen in Figures 9-11. It should be noted, that all compartments of the model ship do not all have the grade 60, 30 and 15 boundaries. This leads to zero results and in occasional lower values in the graphs. Thus, figures 9-11 generally present the ballpark of probabilities as a function of floor area, rather than exact probabilities.

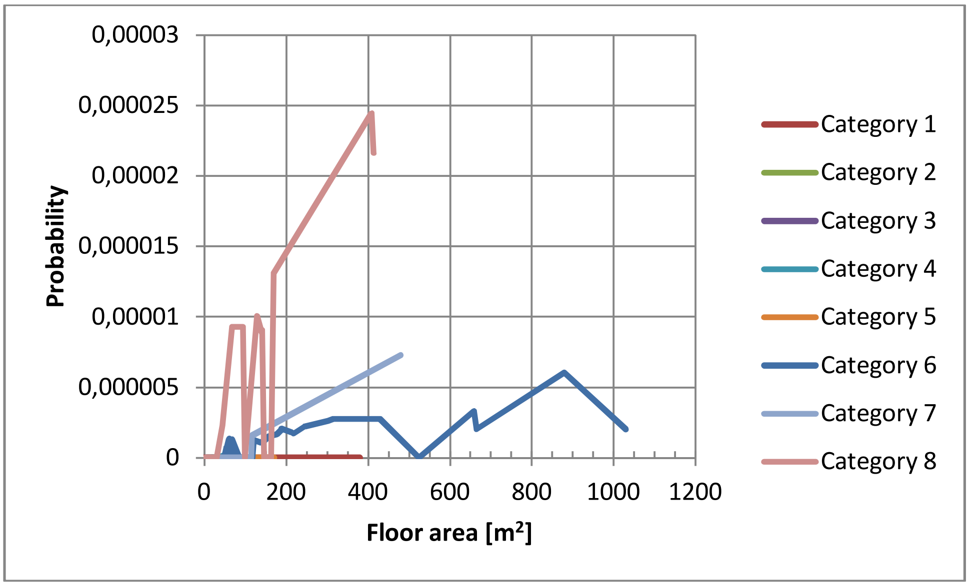

Figure 9. Model ship boundary penetration probability, 60 min.

It can be seen from figures 8-11 that category 8 fires lead to flashover and boundary penetration most probably. Category 8 fires have the highest possible fire growth rate and the highest amount of combustible materials inside the compartment. These parameters cause the most severe fires. In both figures 9 and 10, category 8 boundary penetrations have equal probabilities. In other categories, a small difference between grades 60 min and 30 min boundaries can be noticed. As can be expected, grade 30 min boundaries are penetrated more often, although the difference is not big.

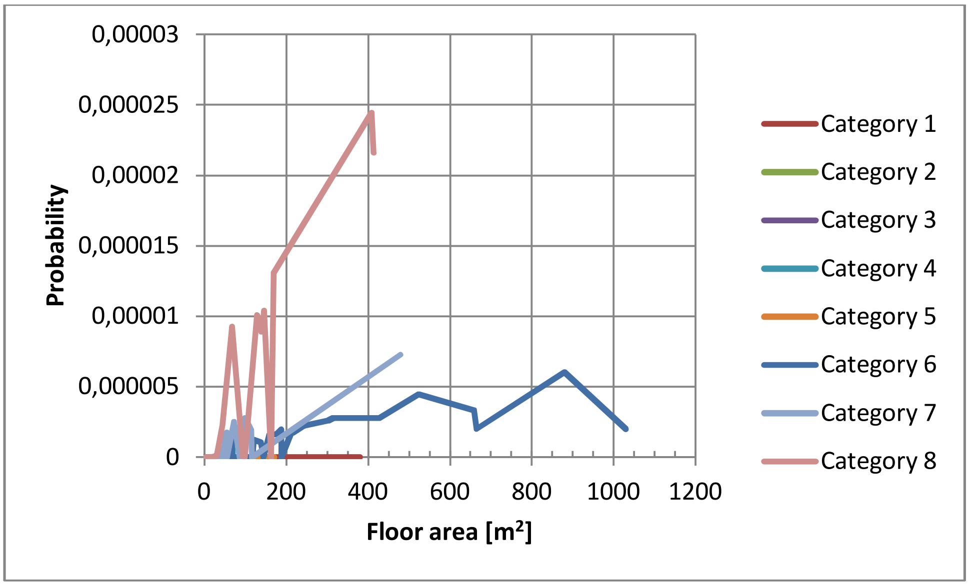

Figure 10. Model ship boundary penetration probability, 30 min.

Probabilities of boundary penetrations between grades 30 min and 15 min boundaries do not vary a lot. The lack of higher boundary penetration probabilities in figure 11, especially in category 8 fires, originate from the lack of grade 15 min boundaries in the largest compartments. Differences between probabilities of boundary penetrations between the boundaries in consideration were surprisingly small. As mentioned before, if sprinklers are activated before flashover or boundary penetration, such will not even occur in PFS simulations. If the sprinklers are not activated, actions of the ships' fire brigade determine the fire development. In the cases where flashover occurred, the ships' fire brigade reached the fire site too late or suppression was determined as unsuccessful in the simulations. As for boundary penetrations, the time to reach boundary penetration is longer than the longest fire brigade response time. This means that in cases, where boundaries were penetrated, suppression was determined to be unsuccessful. In most cases, there is enough combustible materials in the compartments to enable boundary penetration of grade 60 boundaries, if the fire can develop freely. The abovementioned reasons lead to a situation, where the differences between probabilities of boundary penetration between differently graded boundaries are minor.

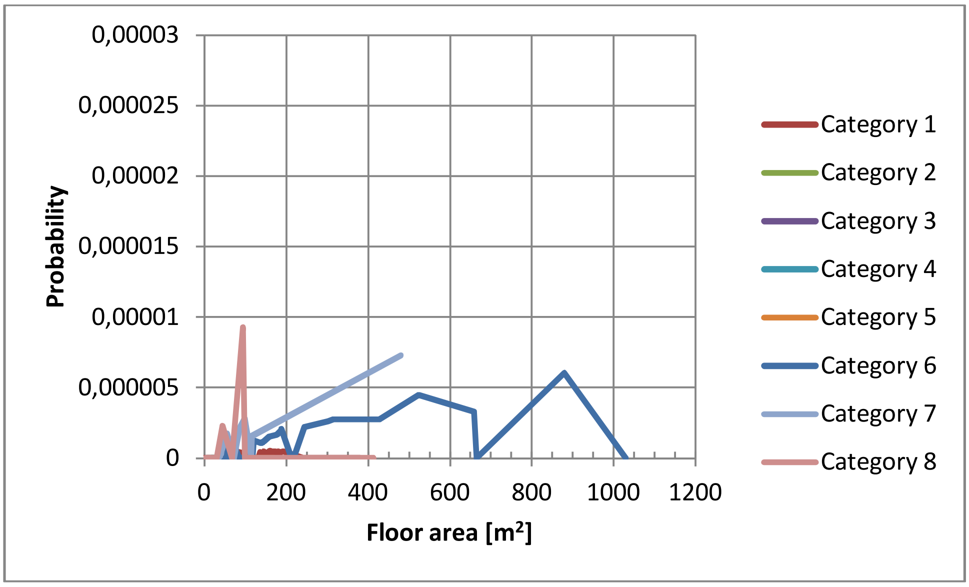

Figure 11. Model ship boundary penetration probability, 15 min.

The following phase was to collect the ship specific attributes needed for the resilience module. Once all of the attributes were collected and fed into the RM, the disabled calculation sheets were enabled again, and FRI of the model ship was ready. Obtained sub-indexes and overall FRI are presented in Table 12. In the overall FRI it should be noted, that due to the exclusion of the evacuation module, the importance weight of 0.5 was given for both fire and resilience module.

Table 12. Case study results.

Module	**Sub-Index**
Fire	0,081144
Resilience	0,214989
FRI	0,296134

The chosen model ship is rather small in volume and in number of spaces onboard, if compared to a large modern cruise ship. This leads to a situation, where the impact of the sub-index from the fire module is quite small, as the additive weight method is used, and the model is prepared to be used with large cruise ships.

It can be concluded, that the model works as intended, and no surprises were encountered, except the longer than expected calculation times.

<u>*FRI*</u>

In this case study, an FRI score of 0,296 was obtained. By itself the FRI score does not represent anything or mean anything. The performance of the ships' FRI score can be evaluated when it is compared against the FRI scores of other similar ships. The same principle applies to sub-indexes. As the real value of the model developed in this thesis is obtained, when multiple ships are analyzed, or when the design of one ship is analyzed.

6.1 Model sensitivity

In this chapter, the model sensitivity to different parameters is studied and results are discussed. Holistic sensitivity analysis, which covers all relations between the parameters, their plausible value ranges and effects on the results, does not fit into the scope of this thesis. The scope of the sensitivity study is to verify the effects of parameter changes to the results. In the sensitivity analysis, only the effects of parameters, which are intended to be modifiable according to the ships' properties, are analyzed.

The model ship was used for the sensitivity study as well. The amount and diversity regarding the floor area of SOLAS category 8 spaces was not enough to ensure a reliable sensitivity study. To increase the accuracy of the sensitivity study, the sample size had to be increased. In order to increase the sample size, all the spaces of the model ship were changed to be of SOLAS category 8, thus being included in fire category 6.

A specific sensitivity RM was created, where all spaces were categorized as SOLAS category 8 spaces. From this, probabilities of flashover and boundary penetrations were recorded. These results were used as a baseline for the sensitivity study.

The general approach was to run multiple simulation sets in PFS, where one parameter was varied. Then, results from each simulation set were imported into the sensitivity RM. Changes in probability of each measured parameter was then observed.

6.1.1 Fire growth rate

The effect of the fire growth rate was investigated by doing multiple simulation sets with different fire growth rates and analyzing the effect on the probability of flashover and boundary penetrations. Unlike in the actual model, in each simulation set, the fire growth rate was kept constant in PFS to ensure as definitive results, as possible. The following simulated fire growth rates were those used in the model; MEDIUM, FAST and ULTRA FAST.

Changes in ship-scale probability of flashover and boundary penetrations are presented in Figure 12. The results are in line with the expectations. Probability of boundary penetrations increases with the fire growth rate. In a normal fire category 6 simulation and thus in the baseline results, the fire growth rate is varied triangularly between FAST and ULTRA FAST. Thus, a slight rise in the boundary penetration probabilities with the ULTRA FAST fire growth rate was expected, as well as negative results with other fire growth rate values.

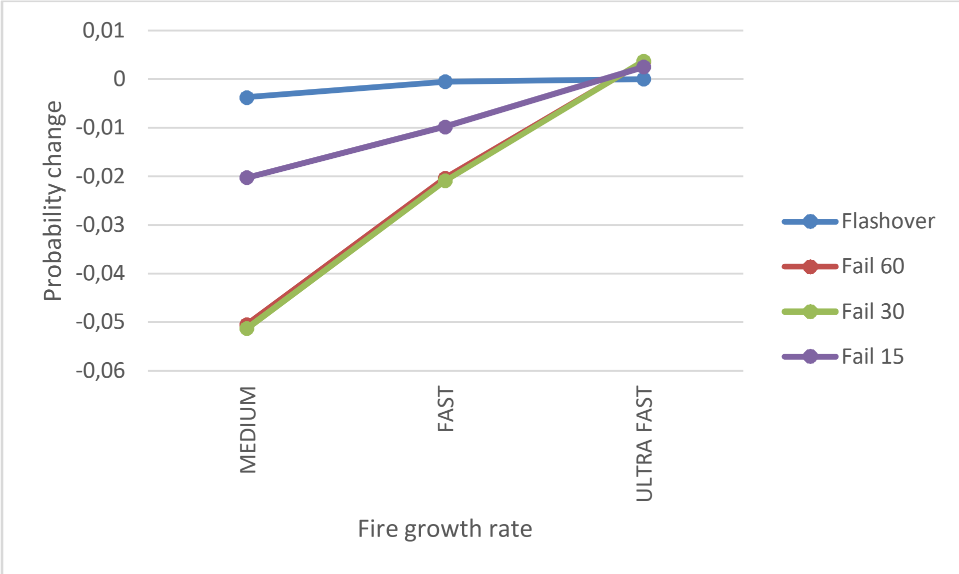

Figure 12. Fire growth rate, sum of probability change.

In Figure 13, the average percentual change of probability of flashover and boundary penetrations for individual spaces is presented. The results are as predicted. As the MEDIUM fire growth rate is not included in a regular fire category 6 fire, a larger variation of probabilities is observed with MEDIUM fire growth rate.

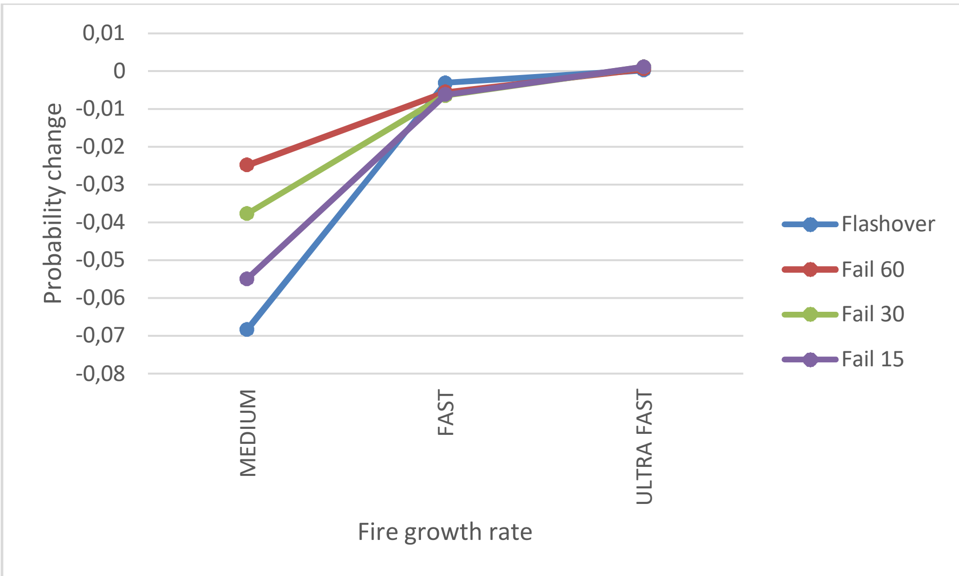

Figure 13. Fire growth rate, average percentual probability change of individual spaces.

6.1.2 Fuel load density

Fuel load density was assessed with the same principles as used above with the fire growth rate. Category 6 fires were used and other parameters than the fuel load density were kept constant. Fuel load densities of 15 kg/m^2, 25 kg/m^2, 35 kg/m^2 and 45 kg/m^2 were investigated.

Ship-scale probability change of the assessed variables is presented in Figure 14. Fuel load density, sum of probability/index change. The results are not in line with the assumptions.

The original assumption was that the probabilities of boundary penetrations would increase with the fuel load density. A notable difference in probability was observed only with insulation category 60 boundary penetrations with 15 kg/m^2 and 25 kg/m^2 fuel load densities. And against the assumption, other probabilities than boundary penetration of insulation category 60, decreased with the highest fuel load density, 45 kg/m^2.

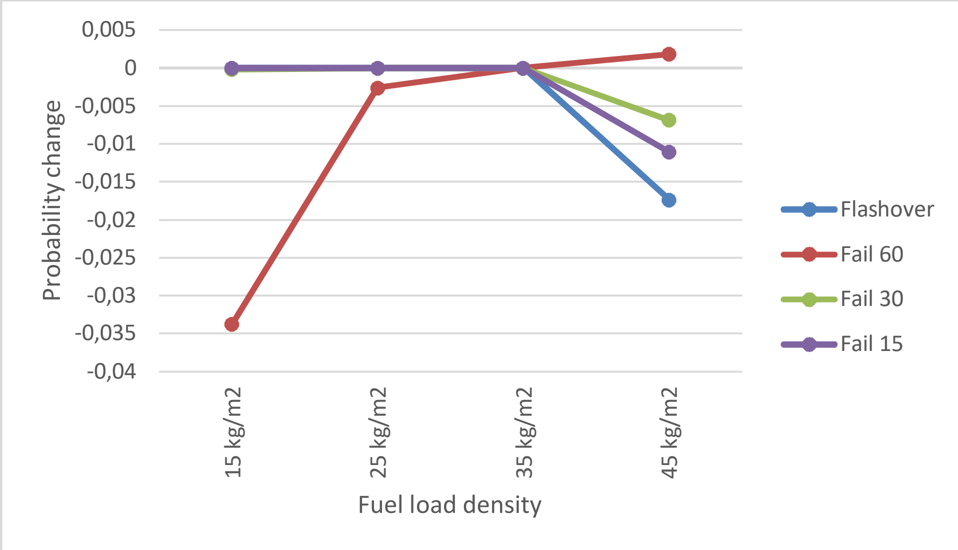

Figure 14. Fuel load density, sum of probability/index change.

In Figure 15, fuel load density, the average percentual probability change of individual spaces is presented. If compared to ship-scale probability change, a slight difference is observed with insulation category 30 boundary penetrations with a fuel load density of 15 kg/m^2. However, the change vanishes in ship-scale.

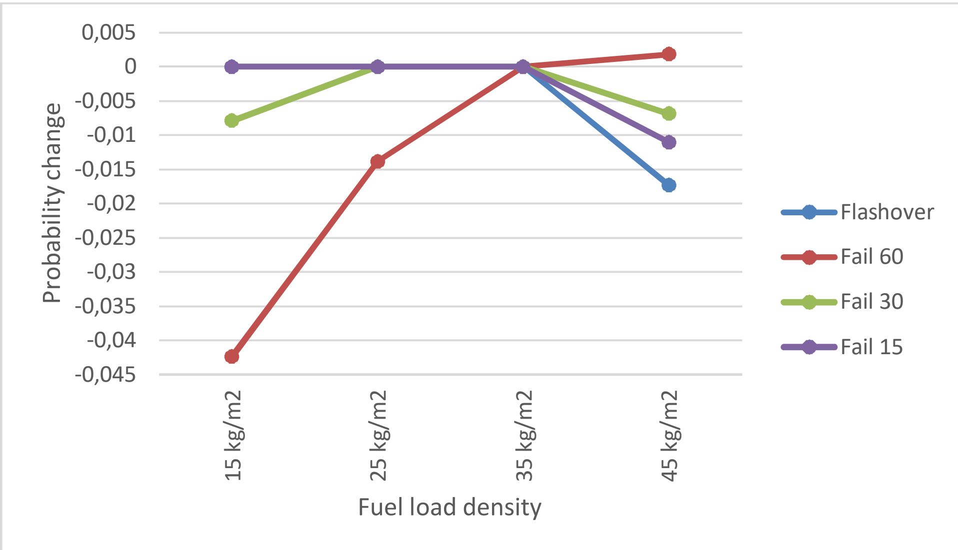

Figure 15. Fuel load density, average percentual probability change of individual spaces.

More in-depth sensitivity analysis is required for the effect of fuel load density. If more detailed sensitivity analysis leads to similar results, a root cause analysis must be performed to determine the reason for the unexpected behavior of the probabilities.

6.1.3 Sprinkler reliability

Sensitivity of the model regarding sprinkler reliability was evaluated in the same manner as fire growth rate and fuel load density. Fire category 6 was used and other parameters were kept constant. Sprinkler reliabilities of 92 %, 94 %, 96 %, 98 % and 100 % were analyzed.

Ship-scale probability changes are presented in Figure 16. Sprinkler reliability, sum of probability/index change. The results are reasonable and in line with the expectations. In practice, a linear correlation in probability change is observed in the results.

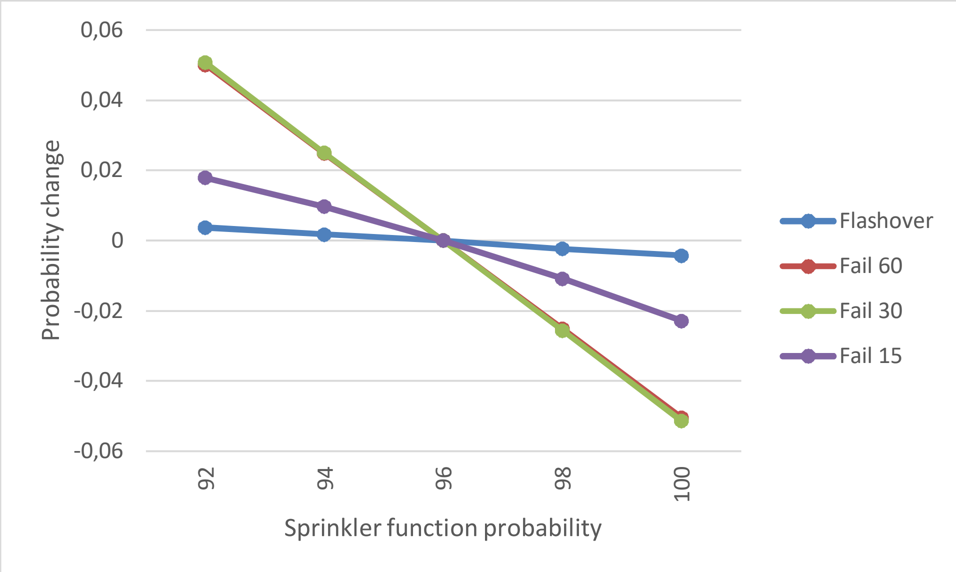

Figure 16. Sprinkler reliability, sum of probability/index change.

In Figure 17, Sprinkler reliability, the average percentual probability change of individual spaces is presented. Here slight differences between the measured variables can be observed. Most notable is the change in probability of flashover, which forms a slight S-curve in the figure, if compared to other variables, which are varying more linearly.

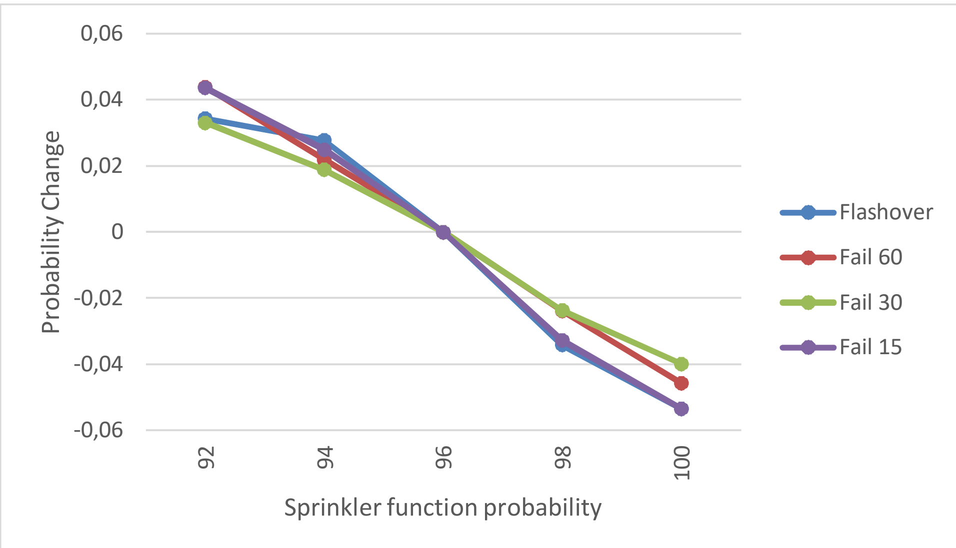

Figure 17. Sprinkler reliability, average percentual probability change of individual spaces.

6.1.4 Fire department proficiency

The sensitivity of the model's results to the fire department proficiency level was investigated by conducting a full FRI analysis for the model ship with two different fire department proficiency levels. The levels used were *Average department* and *Average person with fire extinguisher*. All other parameters were kept constant between the analyses.

Changes in probability of flashover and boundary penetrations are presented in Table 13. The table presents the change from the results with *Average department* to results with *Average person with fire extinguisher*. As expected, the increase in the probabilities is significant. Change in probabilities of spaces, where flashover or boundary penetration was plausible with *Average department,* are not as significant as Table 13 presents. When *Average person with fire extinguisher* is used as a fire department proficiency, the probability of flashover and/or boundary penetration is obtained for a big number of spaces, which did not obtain probability with fire department proficiency of *Average department*. This was expected, as an *Average department* can suppress fires with very high probability, which an *Average person with fire extinguisher* cannot.

Table 13. Effect of fire brigade proficiency.

	FLASHOVER	FAIL 60	FAIL 30	FAIL 15
Sum of probability/index change	0,0462	0,0074	0,0084	0,0074
Average percentual probability change of individual spaces	0,5171	0,0327	0,2190	0,2226

Outcome of the sensitivity study

The sensitivity analysis was performed in order to investigate the effect of the variables in the model. The main purpose was to ensure that changes in the value of the variable would result in a predictable change of the results. Here, predictability includes the assumption that the results changes in the correct direction. For example, as proved by the sensitivity analysis, higher probability of the functioning of the sprinklers leads to a result of less flashovers and boundary penetrations. Less flashovers and less boundary penetrations then, on the other hand, lead to a higher FRI score.

All other variables functioned as intended and predicted, except the fuel load density, which needs further investigation.

7 Future improvements

As the most important aspect of this thesis was to develop a functioning model rather than implement the best available techniques and processes for individual aspects of the model, the corners had to be cut in multiple places. The topics, which should first be addressed in future development are discussed in this chapter. Below, the improvements in PFS and RM are divided in their own sub-chapters for the ease of reading.

A common drawback for both PFS and RM, is that both are Excel based. In PFS workbook VBA macros are an issue, as they limit the calculation speed. Also, the row count in Excel becomes a limiting factor, which leads to a need for multiple PFS workbooks. In RM, references to imported database on multiple different sheets are needed. The way that Excel processes these is extremely slow, and the loading times of the workbook when the full database is in use, are unacceptable.

Due to the abovementioned reasons, building the model with another software or with a suitable programming language, would be a major improvement. One possible approach could be designing a specific NAPA manager for this application. The use of NAPA would be preferable, as the data for the model are mostly obtained from NAPA. As a side-benefit, the model could be easily updated, when the ship design progresses or changes, without the need to change parameters manually in RM or PFS.

The largest issue, which should be considered carefully when choosing the software platform, based on which the model would be updated, is the execution of the LHS sampler. Developing a correctly working LHS sampler is a major task, and some available platforms might not be suited for it. Also, the platform should enable fast calculation speed and a big number of iterations, from where specific data are saved. In addition, the mathematical parts of the model should be easily modifiable.

7.1 PFS future improvements

Should it be of desire to develop the model in a more realistic direction, the most obvious future improvement is to validate the outcomes of the fire scenarios. Now, proven formulae are used to model the compartment fire, but whether occurrences of flashovers and boundary penetrations are realistic, they are not validated. This validation process should include in-depth review of real-life fires, their consequences and an extensive number of CFD analyses of fires within different types of spaces onboard cruise ships.

As stated in section 4, the formulae designed to model fully grown fires and flashovers are not verified to be used in complex large spaces. Currently, in practice, CFD simulations are the only way to assess fire growth in such spaces. If new formulae or other methods become available, they should be utilized in PFS. Another option could be to exclude the large spaces from the simulations and to give them qualitative score based on expert judgement.

In the mathematical model, which is used for calculation of temperature in the initial space, the effective heat transfer coefficient h_k plays a large role. Thus, a realistic value for h_k is desirable. The value of h_k should be made temperature depended. Currently, h_k is time depended, which is not fully realistic, as the heat loss through the walls depends on the temperature difference between the wall elements and the room temperature. If the h_k would be made temperature depended, different h_k development curves for different size of spaces might not be needed. This is due to the fact that the average temperature within a compartment is proportional to the energy that the fire has released. Heat transfer to a steel bulkhead or to a deck is depended, besides the fire properties, on the insulation class of the steel member. Thus, different h_k development curves should be developed for different insulation classes.

Currently, fire is assumed to spread to adjacent spaces, when the temperature on the cold side of the bulkhead or a deck reaches 160 °C. This is a conservative assumption, as most materials and items found onboard a ship do not ignite at such temperatures. Another point is that an item should be in contact with the bulkhead or deck in order to be exposed to such temperatures. If the item is not directly in touch with the bulkhead or a deck, the heat is lost in radiation and convection. The limit was set to 160 °C, as no data were available for insulation performance and cold side temperature development beyond the SOLAS requirements. To make fire spread to adjacent spaces more realistic, cold side temperature development with different types of insulations should be studied. The best approach would be to conduct actual burning tests and some CFD simulations with different types of fires and scenarios. As a goal to reach different cold side temperatures, a time-temperature product of the fire in the initial space should be recorded. This way, the results would be easy to update in the model.

Compartment temperature decay after the fire has started to decay, should be refined. The current mathematical model allows compartment temperature to start to decay simultaneously with the fire. In reality, the temperature decay starts sometime after the start of decay of the fire. Changes in the mathematical model is not a difficult task, but a reasonable way to predict when the temperature decay starts, was not found. A possible approach could be to simulate different types of compartment fires and to record the decay of fire and the decay of temperature. From the results, a suitable mathematical model should then be derived.

The probability of success in fire suppression by the crew's firefighting brigade is depended on the flame/heat area at the time of intervention. This approach was obtained from land-based applications and research. The method of predicting flame/heat area at the time of intervention is based on pool fire. No better alternative was available, thus the pool fire approach was used, even though it is not a realistic representation of a compartment fire. The main problem of this approach is that it is designed to predict outdoor pool fires. As of, it does not take into account more effective radiative heat flux from a ceiling boundary of a compartment, which accelerate fire development and largens the flame/heat area. To combat this issue in the model, a more suitable approach of determining the flame/heat area should be implemented. Another alternative would be to study the topic in more detail and develop some sort of fire escalation factor, which would represent the more rapid fire development in a compartment versus an outdoor pool fire.

Relating to the above-discussed topic, four plausible performance levels for the crew firefighting team are available in the model. Probabilities of success of suppression with a given, encountered fire/flame area are obtained from land-based statistics. These statistics might not represent truthfully the performance of the shipboard fire brigade performance. Land-based fire departments can be assumed to be more proficient in actual firefighting, as onboard a ship, a part of the crew is educated for firefighting purposes, besides their other tasks. On the other hand, onboard a ship, the crew fully knows the site, and has detailed strategies to combat different kinds of fires onboard. Also, water is mostly available from multiple directions and boundary cooling, for example, should be easily organized. Also, the time to reach the fire site varies less onboard a ship. The longest reach times of land-based departments are not faced onboard a ship. Due to these and multiple other differences between land-based and shipboard firefighters, the comparison of proficiencies is a difficult task. A way to compare the proficiencies would be to compare shipboard success of firefighters as a function of heat/flame area to those of the land-based fire fighters. Unfortunately, such data are not available. If such data would become available, comparison and refinement could be done. Themelis et al. [23] used a reduction factory for land-based performance figures. These were not implemented into this model due to the lack of reasoning and evidence.

The sensitivity study regarding fuel load density resulted in some unexpected results, which should be assessed in more detail. The assumption was that as the fuel load density increases, so does the probability of flashover and boundary penetrations. In the sensitivity study, probabilities of flashover and boundary penetrations decreased with the highest fuel load. Due to time restrictions, an in-depth root cause analysis could not be done, and any simple answer was not found.

7.2 RM future improvements

In the resilience module, attribute weights were generated from numeric pairwise comparisons, which were done by the same professionals, who participated in the first part of the questionnaire. As discussed before, consistency ratios of comparisons conducted by individual attendees were not satisfactory. In reality, the proposed 10 % margin is most probably unattainable. However, in the future development, some iteration in matrix generation would be most definitely desirable. Only two out of nine attendees attained a consistency ratio below 10 %, the rest were higher, and some were considerably higher. Iteration should be focused on the evaluations with the highest inconsistencies. Iteration should be done, of course, by the original answerer. If the greatest inconsistencies would be revisited and more consistent comparisons were to be achieved, the overall consistency between the individual comparisons would be better. This would lead to more reliable attribute weight values.

The amount of combustible materials is an important factor in fire simulation. In the case of compartment fires, it mainly determines how long the fire lasts before it starts to decay, if no suppressive actions against the fire are taken. The length of the fire becomes an important factor, when automatic suppression fails to activate or fails to suppress the fire, and the ship fire brigade fails to suppress the fire. In this case, the length of the fire is a factor of whether the fire will penetrate insulated boundaries or not. For the purposes of this thesis, expert opinion was used in assigning the average amount of combustibles per square meter within each SOLAS category. A better way of determining the amount of combustibles within different SOLAS category spaces would be to investigate statistics of the materials and items in the built ships. With a more accurate amount of combustible materials, more accurate predictions from fire consequences could be made.

Due to time concerns, a ship-scale evacuation module must be developed as a part of future work. As evacuation is an important part of the overall fire safety of the ship, a ship-scale evacuation module must be developed before the model is taken into use, specifically for comparing the fire safety levels of different ships. For individual space evacuation a simple hydraulic model, as presented in this thesis, is sufficient. Also, in the first part of ship-scale evacuation, a method for assessing evacuation to assembly stations was presented earlier. The most challenging parts of ship-scale evacuation are embarkation, evacuation from assembly stations to lifeboats and MES. The most reasonable approach would most probably be, to try to emulate results obtained from the evacuation simulations, as was done with evacuation to assembly stations. A simple way of presenting the actual reality would be a much more demanding task. The main issues are, when passengers are leaving the assembly stations and the actual passenger loading into lifeboats or MES. There are generally two strategies used in embarkation. In the first strategy, all passengers are allowed to simultaneously proceed freely from the assembly stations to lifeboats or to a MES. In the second strategy, passengers are guided in control groups from the assembly station to lifeboats or to a MES. Here, both approaches should be built into the model to enable a cruise line specific approach. The issue in simulating passenger loading into lifeboats or to a MES is that plausible and attained loading speed varies between different lifeboats and MES systems. One plausible approach could be to just use the loading factor provided by the supplier of the lifeboat or MES.

The walking speeds, which are used in evacuation module, when calculating the evacuation time to assembly stations, were obtained from [49]. A more accurate representation of the results from actual evacuation simulations would be obtained, if the conducted evacuation simulations were investigated. In future work, the walking speeds should be modified to match those, which in actual simulations produce the 95-percentile results. This would require investigation of evacuation simulations from multiple different ships. From the obtained walking speed, an average should be derived, which could then be used in the model.

8 Summary

A need for a tool, which could be used for comparing the overall fire safety levels of different ships and to quantify the change in the fire safety level of a ship, when the design is changed, was recognized. Some previous attempts have been made, but tools or any software have not been made available. Another problem of previous attempts has been the use of too theoretical approaches for current practical use.

The scope of the thesis was to develop a model in order to holistically evaluate the cruise ship fire safety and to identify the main attributes, which would be needed for such a model. One important aspect was also the ease of use and the ease of obtaining the initial space attributes of the ship to be analyzed.

In the early phase of the master's thesis process, it was decided, that initial ship specific space information should be obtained from the NAPA model of the ship. Applicable macros were created to enable exportation of the needed attributes to Excel. This enables easy and fast exportation of initial space data of the ship under evaluation. As the process is fast forward, updates in the design are also easy to import to the model.

After evaluating different plausible approaches to build such a model, fire risk indexing was chosen. Fire risk indexing offers an easy way of coupling quantitative and qualitative attributes, which was an important aspect regarding the topic. The model itself is constructed from three modules; fire safety, evacuation and resilience. The overall performance of the ship under evaluation is the combined score from each module. The fire safety module assesses the probability of such a fire, where at least the initial space would be lost. The evacuation module assesses the evacuation of the whole ship. It should be mentioned, that the finalizing of the evacuation module was left out for future work due to difficulty in assessing reliably the embarkation phase. The resilience module assesses the ships' capabilities of surviving large fires where one or two main fire zones are lost.

The most effort was used in the development of the fire module. An approach, where two workbooks are used was adopted. The risk model workbook includes all three modules and is used to evaluate each space onboard and to form risk values. The probabilistic fire simulator workbook is used to simulate different design fires with ship specific parameters. These results are then imported to the risk model workbook, where the fire safety module utilizes the results from the simulations in order to derive space specific fire safety scores. One noticeable issue observed during the model development was that the calculation speed of Excel is slow in tasks needed for the model. This results in long simulation times in the probabilistic fire simulator and in long updates in the risk model. However, as the model includes two workbooks, in the case of one ship project, only one set of simulations with probabilistic fire simulator is needed, as changes in the space attributes of the ship can be imported straight from NAPA to the risk model. This way, the implementation of design-changes takes only minutes, once the initial model is created.

A case study was performed using a modern cruise ferry. In the case study, the evacuation module was disabled due to the lack of an embarkation module, and risk weight values were changed accordingly. The purpose of the case study was to test the model and to ensure the functioning of the fire safety and the resilience modules in realistic application. Apart from the longer than expected calculation times, the model worked as intended.

After the case study, a sensitivity study was performed. The scope of the sensitivity study was to verify that changes in the variable parameter would affect the end result in a reasonable and predicted manner. Some surprising results were obtained when the fuel load density was varied, which needs further investigation. Changes in other parameters affected the outcome as expected.

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Appendices

Appendix 1. Questionnaire answer template

Most important items or features to preserve during or after a large fire (1-2 MVZ) onboard a cruise ship

Example

Item or feature: Availability of lifeboats
Why is this item or feature important: If conditions onboard the ship become worse, evacuation using lifeboats might become necessary.
What affects preservation of this item or feature: Longitudinal distribution of lifeboats.

1. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

2. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

3. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

4. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

5. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

6. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

7. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

8. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

9. **Item or feature:**

   Why is this item or feature important:

   What affects preservation of this item or feature:

10. **Item or feature:**

    Why is this item or feature important:

    What affects preservation of this item or feature:

Appendix 2. Comparison template

Intensity scales		
Intensity of importance on an absolute scale	**Definitions**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity ove another is of the highest possible order of affirmation
2.4.6.8	Intermediate values between the two adjacent judgements	When compromise is needed

Comparisons			
A	**If A is more important than B**	**If B is more important than A**	**B**
Emergency power			Fire fighting systems
Emergency power			Availability of LSA
Emergency power			Crew emergency education/skills
Emergency power			Internal communications
Emergency power			External communications
Emergency power			Fire main availability & capacity
Fire fighting systems			Availability of LSA
Fire fighting systems			Crew emergency education/skills
Fire fighting systems			Internal communications
Fire fighting systems			External communications
Fire fighting systems			Fire main availability & capacity
Availability of LSA			Crew emergency education/skills
Availability of LSA			Internal communications
Availability of LSA			External communications
Availability of LSA			Fire main availability & capacity
Crew emergency education/skills			Internal communications
Crew emergency education/skills			External communications
Crew emergency education/skills			Fire main availability & capacity
Internal communications			External communications
Internal communications			Fire main availability & capacity
External communications			Fire main availability & capacity